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Synthetic fuels in aviation – Current barriers and potential political measures

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Abstract

Alternative fuels can contribute to sustainable air transport since these fuels reduce aviation's climate-relevant emissions. Most promising options from today's point of view are: biofuels and synthetic fuels (power-to-liquid, short: PtL or e-fuels). Results from a supply perspective show that biofuels are advantageous in the short term while synthetic fuels could be favorable in the long run. As it would certainly be too costly to finance a transitional biofuel system, it might be better to prioritize the use of synthetic fuels from the start. Due to the international character of aviation, the future production and use of synthetic fuels in aviation is a global issue. This paper investigates the following questions: Which are the current barriers to the use of e-fuels in air transport? Which political measures could facilitate the use of e-fuels?

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1. Introduction

Air transport is expected to grow at about 4% p. a. until 2050, depending on the world region (Airbus, 2018). Since aviation contributes to climate change, it is important to reduce its' climate relevant emissions. However, compared to, e.g., road traffic, air transport is more difficult to decarbonize (e.g., Searle et al., 2019). One option to reduce climate relevant emissions of the sector is an increasing use of synthetic power-to-liquid (PtL) fuels. According to, e.g., Schmidt et al. (2016) or Searle et al. (2019), this can be regarded as a promising long(er)-term strategy to significantly reduce carbon emissions.

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Because of the long lifecycles of existing infrastructures and aircraft and engine technologies, a (yet) very limited range of applications for new technologies (like the direct use of renewable electricity for electric propulsion) and a need for globally uniform technical and operational standards, it would be too costly to achieve a transition to other low carbon forms of energy supply, such as hydrogen, in the foreseeable future. In addition, given the long time span to introduce entirely new aircraft designs based on hydrogen into commercial operation of at least 20 years and the limited remaining carbon budget available for the aviation sector, a focus on a hydrogen rather than drop-in fuel path would most likely result in significant 'waste' of this carbon budget. In other words, even though post-carbon e-fuels are still quite expensive today, they are more likely to provide aviation's contributions to global carbon efforts much earlier than any from a hydrogen path.

Moreover, it is difficult to find an energy carrier that has similar characteristics like jet fuel with regards to energy content, usability and technical viability. In this regard, the aviation system differs from ground transport, where even at today's technological level the direct use of electricity as energy carrier can be regarded as a proven concept.

The introduction of the global market-based measure "Carbon Offsetting and Reduction Scheme for International Aviation" (CORSIA) in 2021 underlines that technological and operational measures alone are insufficient to limit annual carbon emissions at constant levels ("CNG 2020" goal), let alone to achieve a net decrease. Hence, besides an increasing use of carbon neutral fuels, we cannot see any realistic technology option to significantly reduce total carbon emissions from aviation in the medium to long term (see also Flightpath 2020, 2018).

PtL fuels have the advantage that existing infrastructures, vehicles and engines can be further used, allowing a transition towards these fuels to take place gradually as blending with conventional jet fuel is possible at least up to certain drop in levels (e.g., Schmidt et al., 2016). If more e-fuel quantities become available in the future, the actually used fuel blends could have higher synthetic shares as time progresses.

Against this background, this paper will focus on barriers to the use of e-fuels in aviation, and on potential political measures to overcome such barriers, while alternative technology options are not further investigated. However, as hydrogen is needed to produce synthetic e-fuels, any increasing use of synthetic fuels is on a similar technological pathway as the direct use of hydrogen. There also may be synergies between the e-fuels and hydrogen pathway in a way that parts of the process change can later be used for the direct use of hydrogen as well (on the prospects of hydrogen-powered aircraft see, e.g., Khandelwal et al., 2013).

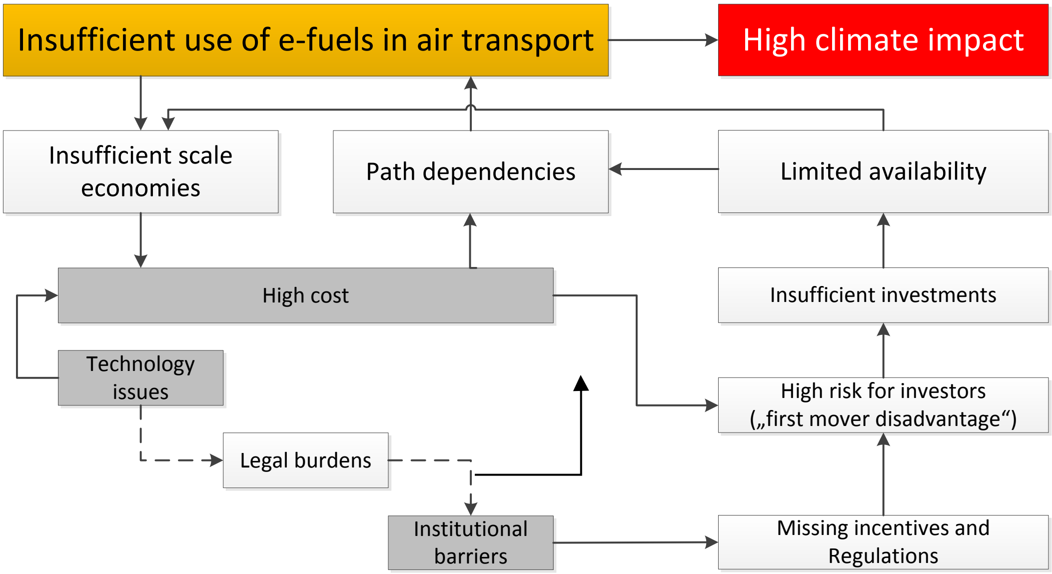
2. Existing barriers to the use of e-fuels

A number of key barriers to the use of synthetic fuels in the air transport sector exist to date. Figure 1 presents an overview of these main barriers which the authors have compiled from literature and based on stakeholder interviews.

2.1 Technological issues

In principle, any provision of jet fuel types not meeting the globally relevant fuel standards would raise the question of compatibility and probably require a costly, ubiquitous duplication of fuel provision infrastructures. The same applies to the introduction of engines requiring other fuel types. Hence, we can preliminarily conclude that a successful market entry of new fuel types requires 100% compatibility with existing fuel types.

Figure 1. Main barriers to the introduction of synthetic fuels in aviation



Source: DLR.

Energy supply to aviation is a well-attuned, running system characterized by ubiquitous availability of international jet fuel standards (mainly Jet A in the US, Jet A-1 outside the US, and TS-1 in former Soviet states) for aircraft gas-turbines. These standards mainly differ with regard to their flash point minima and/or freeze point maxima but are compatible with virtually all current and historic jet and turbofan aircraft. Piston engines, which are commonly used in light aircraft but barely in commercial air transport, make use of Avgas. Jet A fuels must reach ASTM (ASTM International, formerly "American Society for Testing and Materials") specification D1655, while Jet A-1 has to additionally meet British specification DEF STAN (UK Defence Standardization) 91-91 and IATA Guidance Material (Kerosene Type), NATO Code F-35 standards (see, e.g., Aviation Jet Fuel Information, 2019; ASTM International, 2019a).

ASTM D7566 provides standards for the manufacture of aviation turbine fuel consisting of conventional and synthetic blending components (ASTM International, 2019b). Its annexes contain specifications for the different pathways that have been approved. Sustainable aviation fuels (SAF) have to be blended with conventional jet fuel to meet the ASTM D7566 requirements, which allows blending of FT SPK and HEFA SPK up to 50% with conventional jet fuel (10% for SIP SPK) (IATA, 2015). As things stand currently, blending shares above 50% may not be safe as synthetic fuels do not contain any aromatics. Those aromatics, included in kerosene, are not required by the engines but by current O-Rings to function properly (Liu et al., 2011; Ewing, 2011; Graham et al., 2013).

To sum it up, technologically, there is already enough scope for a significant drop-in use of e-fuels through blending. This way, hardly any duplication of infrastructures at the airport level, or changes to the airlines' operational routines would become necessary. However, Searle et al. (2019) point at the fact that certification can be a barrier for novel fuels, as ASTM requires 'up to 235,000 gallons of new jet fuels to be tested', which seems a too large amount of new fuel to be produced just for R&D purposes. If new fuels are produced in very similar ways compared to fuels which are already approved, this hurdle is however reduced to only some 10k or 100 gallons of fuel to be tested, respectively (see Searle et al., 2019, p. 9; Commercial Aviation Alternative Fuels Initiative, 2013).

2.2 Cost of synthetic fuels

Fuel costs are one of the most important cost items for most airlines. On average, cost shares for fuel reported by 28 IATA airlines for 2012 amount up to one third of total airline input costs (Ferjan, 2013). This already leads to the main barriers to the use of PtL fuels and other sustainable aviation fuels: Unless synthetic fuels are available at similar or even lower cost than conventional fuel or pushed by effective political regulation, fuel suppliers and airlines are unlikely to blend conventional fuels with more environmental friendly fuel types.

Hence, to be attractive for suppliers and users, cost of synthetic fuels would have to be equal to or lower than those for conventional fuels – at least if identical performance levels are assumed. Existing regulatory costs would also have to be considered, e.g. the obligation to offset certain shares of CO_2 emissions from conventional fuel under the forthcoming CORSIA scheme, which would not apply to decarbonized fuels.

However, as we will also discuss below, due to a more complicated, multi-stage production process, required feedstock and (input) energy, and (yet) a lack of large-scale plants, e-fuels come at significantly higher cost than conventional fuels. Also, they are expected to remain more expensive in the future despite efforts to lower unit costs by increasing economies of scale and introducing advanced technologies:

- According to Finnish company Neste, sustainable aviation fuel is generally 3-4 times more expensive than traditional jet fuel (Berti, 2018).
- This range is also confirmed by DLR which estimates PtL fuel costs of about 2.26 € per liter for 2016, compared to about 0.5 € for conventional fuel (Albrecht, 2017), and by Ludwig-Bölkow-Systemtechnik (LBST) who estimate PtL fuel costs of about 3,245 €/t at today's technological knowledge (Schmidt et al., 2018).
- For 2050, LBST expects significantly lower PtL production costs, which would result in a price of about 1,352 €/t – which would however still be almost twice as high as conventional fuel today.

As a result, potential demand can be considered too low, and any e-fuel market would struggle to develop. Moreover, the relative competitiveness of e-fuels could be affected in the long-run by the development of global demand for mineral oil-based fuels. In the long run, with decarbonisation as a political objective in all areas where liquid hydrocarbons are currently being used, demand for mineral oil could drop significantly. Hence, market price for oil could come under severe pressure and therefore widening the price gap between mineral oil-based fuels and e-fuels.

2.3 Institutional and legal barriers

Another burden is the lack of global or at least regional strategies towards the implementation and promotion of e-fuels in air transport and elsewhere, along with the required institutional frameworks in form of regulations. Also, possible legal burdens regarding the use of e-fuels would have to be sorted out.

To date, we cannot identify any regulation designed to raise the share of e-fuels in aviation. To reduce barriers to the use of e-fuels, potential incentives or regulations shall address different issues and levers:

- Policies directly raising the use of PtL fuels, like e.g. mandatory PtL blending shares in jet fuel.
- Policies lowering the net production costs (price) for PtL fuels, and associated risks (e.g. potential "first mover disadvantage") like R&D subsidies or investment aids.
- Policies improving the relative competitiveness of PtL fuels in increasing the cost for conventional fuels, like different forms of carbon pricing for CO_2 internalization.

While this paper cannot provide a deeper analysis into the potential legal issues associated with the introduction of synthetic fuels in the aviation sector, we assume that legal challenges will play a major role in the context of regulatory measures that may be introduced to push the production and/or use of such fuels.

As important steps have been made towards the general use of – at least – blended PtL (which is now possible according to ASTM and other certifications), focus should be on, e.g., the following questions:

- To what extent could e.g. compulsory blending quotas for PtL fuels, or other measures, be introduced at the national or e.g. European level(s)?
- Can e.g. Member States, the legislative bodies of the EU or EASA regulate fuel supply in a way that mandatory blending quotas can be introduced, and can all airlines, also from third countries, be forced to use such fuels?

The RED II (Renewable Energy Directive) (see also EU, 2019) requires national implementation and includes aviation. Subject to more detailed legal assessments, this could be a basis for a national solution in case no progress is made at the European level.

3. Potential political measures to facilitate the use of synthetic fuels

3.1 Incentives for the development of synthetic fuels

According to literature, the basic processes for the production of synthetic fuels are well understood. However, further significant efforts are needed to achieve a large-scale application and commercialization at acceptable production cost levels. Even under favorable parameters, it is likely that PtL production in the long run will be more costly than today's jet fuels based on mineral oil.

Key R&D efforts and large scale demonstrators are for instance required in the sector of water electrolysis with renewable electricity, CO_2 extraction from industrial process or CO_2 capture from the atmosphere as well as the development of processes and catalysts for both the Fischer-Tropsch and the methanol route for PtL production. All these elements are ultimately cost inputs for PtL production. Some examples illustrate the long way still to go to realize large scale PtL production. For instance, the world's largest water electrolyser to be built at the refinery in Wesseling, Germany, with a 10MW peak capacity will require an investment of 20 million € with an estimated output of 1,300 tons of hydrogen per year, while the overall refinery requires 180,000 tons of hydrogen for its processes), which, ironically, continue to be produced with the steam reforming process (ITM Power, 2018), resulting in high CO_2 and CH_4 emissions with a high impact on climate change.

Hence, it can be considered that a key element for a progress in PtL production/use is the increase in efforts for research and development of processes and their large-scale commercialization. It seems to be realistic that private investment alone will be insufficient to achieve an accelerated progress with PtL production/use. State support seems to be important, as research and development in the PtX area is subject to market failure. Investments in R&D by private stakeholders are considered as too risky, and therefore not enough funds are spent on the R&D efforts.

Besides subsidies into the R&D of processes, the state could intervene by funding pilot PtX refineries. This could be a valuable proof of concept of the theoretical ideas, in case no private investment is offered. Efforts in this direction are for instance being done by the Joint Technology Initiative Fuel Cells and Hydrogen, which contribute 10 million € to the above mentioned water electrolyser at the refinery in Wesseling.

Incentives for the development of PtX fuels can play an important role to convince investors to invest money into risky projects, which however could yield substantial returns in the long run. An inherent risk to the subsidization of private R&D efforts is free-rider or windfall effects, in case the state would subsidize private efforts, which would have occurred also without state subsidies. Therefore, the incentive structure of any subsidy scheme should be carefully designed.

3.2 Incentives for production of synthetic fuels

Once such key challenges are solved and the most promising technological routes are identified, the large scale production of synthetic fuels could be started. Here, various further challenges emerge.

Two key drivers of PtL production costs are energy input and capital costs for energy generation and refinery facilities. In the center of the PtL production process is electrical energy from renewable sources, which is required for hydrogen production, carbon capture, running the PtL refinery and potentially running of desalination plants for sea water. Hence, PtL production costs will be driven ultimately by energy costs and capital costs for hydrogen production and carbon capture facilities, desalination plants, PtL refineries and initially also renewable power generation plants.

It becomes clear that it would be insufficient to direct the attention only to the aviation sector when trying to develop a successful PtL roadmap, as many elements of energy, industry and transport policy interact and need to be adjusted in order to fit together. For example, there might be other sectors where electrical energy from renewable sources could replace energy from fossil fuels more efficiently (e.g. an earlier cut off of coal-based power plants which generate electric power for general use in households).

More research is required in the areas of hydrogen production and carbon capturing. Research challenges in this area are the increase in efficiency for electrolysis and carbon capturing. Also here, systems aspects may play a large role, e.g. if hydrogen production should be centralized or de-centralized (for instance at individual wind turbines at times when no electricity is demanded by the network). For carbon capture, solutions to efficiency challenges have to be found when it is applied to non-concentrated CO_2 flows, i.e. capturing carbon from the ambient air, which currently is highly inefficient. In a study conducted by Frontier Economics (2018), these elements of a PtL introduction strategy are called “pillar technologies, for which own roadmaps need to be developed”.

From the physical facilities required for the PtL production chain, we can further conclude that a substantial amount of capital will be required to set up all elements of the production chain. With a reduction of capital costs, also the production costs of key input factors for the PtL production chain (electricity, hydrogen, carbon) can be decreased. The capital cost problem could be addressed directly by the state, e.g. in the form of loan guarantees for private investors. Also subsidies for the construction cost of elements of the PtL production chain could be applied, as it was done for instance with the Rhineland refinery 10MW electrolyser, where the Fuel Cells and Hydrogen Joint Undertaking (FCH) of the EU covered half of the 20 million € investment cost (FCH, 2018).

So far, with a considerable number of uncertainties concerning the amortization of investments in PtL infrastructure (technological progress, carbon prices, public subsidy policy to name just a few), one could conclude the presence of market failure. Private investors do not want to become first movers, as changes in framework conditions over the economic lifespan of the projects may render any investments obsolete before they have amortized. Hence, it is logical and economically prudent for the state to act. However, in all cases, it would have to be assessed to what extend other use of public money could generate higher benefits. In order to avoid the market failure emanating from the first mover disadvantage, the state could offer guaranteed prices for PtL fuels. This would create legal certainty for investors and incentives for PtL production. The economic rationale of this instrument has been applied when setting up the German Renewable Energy Sources Act (EEG), which provided investors incentives to invest into renewable power generation. This was particularly important, when wind and photovoltaic energy generation emerged, but still had a relatively high cost disadvantage over conventional electricity generation. A key challenge associated with this instrument is the generation of funds that can be re-distributed to the PtL production. In the EEG system, surcharges are levied on the consumers of electricity and paid to the operators of renewable power generation facilities feeding electricity into the network.

With regards to the incentives to invest into renewable power generation, the EEG system can be considered as successful, as in 2018 more than 40% of electricity consumed in Germany was from renewable sources. However, it is often criticized that the EEG system led to a redistribution of more than 30 billion € from private households to the renewable energy industry (Bundesministerium für Wirtschaft und Energie, 2018).

A similar approach could be developed for the PtL system, requiring users to pay a surcharge to subsidize the production of PtL fuels. While an EEG-like system for PtL fuels in aviation is theoretically conceivable, the question should be raised concerning the compatibility with European and international law. In aviation, bilateral air service agreements govern the legal aspects of commercial air transport between two states. Typically, fuel taken on board for international flights is exempted from taxes and other charges (Umweltbundesamt, 2005). It should be analyzed, whether an EEG-like surcharge would constitute a form of "charges", which would then be excluded in the majority of bilateral air service agreements. Alternatively, any surcharge for the production of PtL fuels could also be levied upstream on the level of fuel producers or distributors. This could potentially avoid any conflicts with aviation law.

Theoretically, it is conceivable that an EEG-like surcharge could be applied for domestic flights only (based on an amendment of national law) or on intra-European flights (based on an amendment of EU law). This, however, would substantially reduce the environmental effectiveness, as according to DLR estimations, out of the total jet fuel used on flights departing Germany of 8.7 million metric tons, only 0.57 million tons are used on domestic flights and 2.8 million tons are used on flights to geographical Europe. However, on the other hand, it may also take some time until production capacities are built up in order to produce enough PtL fuels required to be used on all type of flights.

A key benefit of the surcharge policy instrument is the separation of financial flows for the support of PtL production and the physical use of PtL fuels. In case the physical distribution to all users would be too costly or complicated, users not using PtL fuels physically would still contribute to the PtL production. This resembles the network characteristics of the electricity market, where not all users receive the same amount of renewable energy, but all users con-tribute to the production of electricity from renewable sources with the same surcharge per kWh of electricity consumption.

Finally, also the international dimension of PtL production should be considered. As energy costs will be a major driver of PtL fuel costs, the location of the PtL production chain or parts of it should be considered taking into account the economic efficiency. This could result in production locations for instance around the "sunbelt" of the equator, where photovoltaic electricity generation is beneficial or in places with a particular efficiency for wind power or geothermal energy. Hence, PtL production may also have a favorable impact on economic development for countries that have a potential to participate in international energy projects. Any development aid in this direction could not only have positive impacts on the receiving countries, but also for the consumers of energy in the developed countries.

3.3 Incentives for use of synthetic fuels

Besides research & development and production, political measures incentivizing the use of PtL fuels are the third pillar in the introduction roadmap for e-fuels. One major leverage point is reducing the price differential of conventional fuels and PtL fuels for the users. Even under favorable conditions, it is expected that the PtL production costs will be higher than the costs of conventional fuels on current price levels. Hence, political measures may address this competitive disadvantage of PtL fuels. In principle, several measures could be applied in order to reduce the price differential:

A possible approach could be increasing the costs of emitting carbon dioxide from the use of conventional fuels, while exempting users of any taxes, charges or emissions allowances from the portion of fuel consumption that comes from PtL fuels. In aviation, carbon dioxide emissions are currently priced via the EU-ETS in aviation, where the allowances for emitting one tone of carbon dioxide are currently priced around 25 €/t, although a substantial number of allowances is distributed free of charge to the aircraft operators. From 2021 onwards, car-bon credits for emissions exceeding the baseline of the 2019/2020 average emissions have to be surrendered for all flights between countries participating in the CORSIA scheme. Prices for credits are expected to be much lower due to different reasons. Generally, on the current price levels, incentives to reduce carbon dioxide emissions are relatively low, as one ton of fuel costs around 500 € (March 2019). The emissions allowances required for using one ton of fuel are in the order of 75 €. The actual "surcharge level" is by far lower, as allowances are distributed free of charge in the EU-ETS and the baseline of 2019/2020 average emissions remains without any offset obligation in CORSIA.

As fuel used in commercial aviation remains free of any climate related taxes with the exception of a small number of domestic markets, it is likely that a fundamental change in the taxation regime for petroleum-based fuels would be required in order achieve an effective incentive scheme for the use of PtL fuels. At least for European domestic flights, EU Member States could introduce a tax for fuels used by commercial aviation (cf. Directive 2003/96/EC Art. 14 (2)). Generally, it is perceived that this instrument is not widely accepted by industry and policy stakeholders, as it will result in a direct cost increase for operators. Typical arguments presented in this context are job losses due to reduced travel activity and less revenues from taxes on income, revenues and profits. However, a fuel or carbon tax could be a very effective instrument, as the funds generated could be re-distributed for the promotion of projects fostering the transport and energy transition. However, given the general characteristics of a tax, this appropriation is not guaranteed.

With or without an increase of taxes on petroleum-based fuels, an accompanying measure that could further reduce the differential of end-user fuel prices could be a reduction of or exemption from taxes for PtL fuels. Although fuels used for commercial aviation are widely exempted from taxes and hence a tax exemption of PtL fuels would not constitute a difference to the use of petroleum-based jet fuel, the spill-over effects of such a policy for the aviation sector should not be underestimated.

In case the use of PtL fuels for road transport would be subject to reduced or exempted energy taxation, this could trigger a strong incentive for investments in PtL production capacities. The aviation sector could be a beneficiary of economies of scale in the production, in case the use of PtL fuels in road transport would be incentivized. Aviation consumes only a relatively small fraction of all liquid hydrocarbons sold in Germany (e.g. 8.7 million tons of jet fuel, compared to 18.3 million tons of gasoline and more than 30 million tons of Diesel). The positive spill-over effects are based on the assumption that future PtL refineries can switch production between road transport and aviation uses.

Another effective policy measure would be the introduction of a compulsory blending quota for aviation fuels. This measure would work in analogy to the blending quota applied in Germany for road transport fuels on the basis of the EU Directive 2009/28/EC and German Federal Emissions Law (BImSchG) §37a. Up to now, the blending quota is only applicable to fuels covered by the Energy Taxation Law, where fuels used in commercial aviation are exempted. For air transport, the blending quota will probably cause less challenges than those experienced for road transport. In road transport, a small percentage of vehicles has not been certified to be operated with fuels with a higher content of ethanol (E10), hence it was prescribed that gas stations have to offer two different qualities of gasoline (E5 and E10). In aviation, PtL blends of up to 49% PtL content are considered to be fully complied with the jet fuel specifications published by ASTM. Therefore it is reasonable to assume that all commercial aircraft are certified to use these PtL blends. Any duplication of infrastructures in fuel distribution could therefore be avoided.

A compulsory blending quota could be considered as an effective political measure to promote the use of PtL fuels. Also with regards to dynamic efficiency, a blending quota could be considered as preferential: With a compulsory quota to be set in advance, a signal will be provided to any investors into the PtL market, that it is efficient to develop cost-efficient production processes and mass-production facilities. Also a competition for the most cost-efficient production process could be triggered, in case the blending quota is goal-oriented towards carbon dioxide emission reduction and leaves it to the market to develop the best route and production process to achieve this goal.

The costs for users could remain at acceptable levels, as the following exemplary calculation shows: A 5% compulsory blending quota at an assumed price of initially 3000 €/t for PtL fuel would increase the jet fuel price from today's level of 500 €/t to 625€/t. If this blending quota was applied to all flights departing Germany, a demand for more than 430,000 t of PtL fuel would emerge. Under these assumptions, user costs would increase by about 1.1 billion € (cost difference of 2500 €/ t of fuel times the consumption of 430,000 t). A key advantage of the blending quota is that it could be introduced with a clear signal to investors concerning the required size of mass production levels and could be increased gradually as technological progress leads to falling production costs in order to gain acceptance with stakeholders and to avoid cost increases detrimental to overall economic development. It will nevertheless be challenging to set the schedule and quota correctly, in order to achieve an effective incentive, to consider technological progress appropriately and to avoid a watering down by lobbyism. Generally, the blending quota applied directly at the level of mineral oil producers or distributors, the transaction costs would be relatively low. However, the distribution of PtL fuels might be challenging: For efficiency reasons not all jet fuel at the German airports may have the same PtL content. For instance, it could be the case that a PtL refinery exclusively delivers its fuels to airport A, where an overall blending level of 30% is reached, while at other airports, the blending level would be much less or even zero. In case the PtL quota of e.g. 5% is achieved on average this would be acceptable as far as the environmental effectiveness is concerned. However, the distribution of costs for PtL among users has to be organized in a fair and equal way in order to avoid the competitive disadvantage for airlines operating at an airport with a higher PtL share. Hence, the instrument might need to have elements of compensation payments, which then would look more like the EEG-style surcharge model.

The compulsory blending quota with a cost increase in end-user fuel costs would have some competitive effects, as aircraft operators with a higher share of fuel costs in total operational costs will be affected more intensely by this instrument. This likely applies to long-haul operations, which are generally relatively fuel-intensive. Moreover, with an "artificial" cost increase for jet fuel, airlines may have a higher incentive than today to operate with a practice called "tankering". This means that airlines voluntarily take more fuel aboard on airports with relatively low fuel costs than actually required to operate the next flight segment. This practice is economically reasonable for the operator, when the savings resulting from the price difference for fuel are higher than the costs caused by additional fuel consumption caused by the higher total aircraft mass on departure. From the environmental perspective, tankering is negative, as emissions increase due to higher fuel consumption. A further disadvantage of the blending quota is that it is difficult to achieve any voluntary commitment surpassing the compulsory blending quota. As only one type of jet fuel is delivered, it would be logistically complicated to use fuels with a higher PtL content.

Besides the economic effects associated with a blending quota, also legal aspects have to be considered. The question is if such a blending quota can be made compulsory for the aviation sector and – if this can be affirmed – on which level of legislation such a step can be initiated. The question is, whether a technical specification of jet fuel as PtL blend could be made mandatory on the level of mineral oil producers or distributors, in order to avoid any legal problems in case this would be done at the level of airlines.

Another possible policy measure is the introduction of so-called green certificates. Green certificates could prove that a certain level of PtL fuels are used somewhere in the aviation system, but do not necessarily require that holder of the certificates uses the PtL fuels directly for the own operations. Hence, the main advantage of green certificates is that physical use of PtL and monetary support for the production/use of PtL are split. Hence, any logistical issues with providing the right quantity of PtL fuels at all airports at all times can be overcome. Fuel can be blended according to the level of certificates bought in the overall system (e.g. Germany or Europe). A green certificate system could be made compulsory with a pre-defined level of green certificates to be held (as a "virtual blending quota") or used voluntarily with an individually preferred level of contribution. Certificates are then the means to prove that PtL fuels have been used somewhere in the aviation system. The green certificate system could be regarded as a hybrid-solution between blending quota and surcharge. As an element of the blending quota, the overall quantity of certificates determines the average share of PtL fuel in the system (e.g. Germany or Europe). As an element of the surcharge, the money raised with green certificates is re-distributed to the producers or users of PtL fuels. Hence, these stakeholders are being compensated by the users of green certificates for the higher costs associated with PtL fuels. The voluntary use of green certificates can be found in the retail electricity market, as suppliers want to offer electricity from renewable sources, for which consumers may have an additional willingness to pay. However, due to the network nature of the power grid, it is not physically possible to deliver electricity from renewable sources to every individual household that has bought only "green" energy. However, in the aviation market, a voluntary solution might not work, as the additional costs for PtL are higher by far compared to the electricity sector, where production from some renewable sources is almost on the same level as from conventional power generation. Moreover, owning green certificates might not be a marketing advantage for airlines as it is on the retail electricity market, where customers have developed a relatively high awareness for "green" energy and passengers have on many routes a much smaller choice of airlines than they have in the electricity market.

As with other policy measures the introduction of green certificates should also be checked against the compatibility of the existing legal framework. Again, it would be preferential if such a measure could be applied on the level of mineral oil producers or distributors, in order to avoid the constraints of bilateral air service agreements concerning levies, taxes and charges on fuel. Moreover, on the airline level, there might be only limited acceptance, as airlines are currently obliged to comply with the EU-ETS and CORSIA. A system of green certificates would be a third system in parallel, which might be problematic with regard to transaction costs and the interaction between the different instruments. Also with regards to the number of regulated entities, an upstream approach would be preferential, as there are only very few fuel suppliers, but many more airplane operators. This could ultimately lead to a reduction in transaction costs. Potentially, a pilot-phase could be launched for domestic flights, which are by definition excluded from ICAO's CORSIA, hence no overlap between the two instruments would occur. However, a number of challenges (tankering, documentation of fuel used, low environmental effectiveness compared to all flights, e. g.) still have to be overcome. An interesting approach also could be the interaction with CORSIA, where "eligible fuels" can be credited towards the offsetting requirements. More details on the applicability of these fuels are currently under political discussion, results will become available throughout 2019.

To sum it up, a green certificate system seems to be preferential for a number of issues, for instance the re-distribution of money to users/producers of PtL, overcoming of logistical issues of a uniform blending quota and the given possibility for a gradual implementation.

4. Conclusions

Synthetic fuels would have significant impacts on the environmental footprint of the aviation sector. However, a system transition to e-fuels would require large investments and need a long time. Therefore, it is crucial to analyze any associated advantages and barriers as a basis for developing a roadmap as well as actual political measures to push the use of synthetic fuels, in order to be able to complete such a transition in the long term, say by 2050. Our assessment of possible political measures for the promotion of PtL fuels has shown that on the one hand a variety of measures would be useful. However, on the other hand the international character of aviation makes improvements difficult to realize. Against this background it is recommendable to start with national and European approaches first while at the same time begin negotiating on the ICAO level. Since progress on ICAO level is usually very slow, it would be an alternative to address the mineral oil industry directly instead of ICAO.

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