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A post-carbon aviation future: Airports and the transition to a cleaner aviation sector

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ABSTRACT

There is an increasing global interest in sustainable aviation technologies as a result of concerns associated with the carbon-intensive nature of the industry and the imminence of reaching peak oil. Available options such as biofuels, liquid hydrogen and electric propulsion will not only impact on the design and functionality of commercial airplanes, but also will affect the entire industry from supply through to operation and maintenance. However, on account of the global spread and international nature of aviation, in addition to the lock-in effect associated with existing fossil-fuel driven technology, the present aviation paradigm is not well equipped for a massive or rapid technological transition. This paper first provides an overview of selected available propulsion options, as well as their possible impact on the aviation infrastructure. It then sets out to identify the existing regime players in the aviation transition arena as a means to provide an overview of potential path trajectories, with a view to assessing how airport owners and other salient regime players can either facilitate or hinder the transition to alternative and less carbon-intensive technologies.

1. Introduction

The current propulsion technology used by commercial aircraft will be challenged by the introduction of emissions trading schemes targeting transport, in addition to the imminent reality of peak oil production, with its consequent impact on oil price. Although the petroleum-fuelled jet turbine has dominated commercial aircraft propulsion since the 1960s, it is uncertain whether incremental changes to the existing technological and infrastructural paradigm, as signalled in a recent article by Charles et al. [1] in this journal, will be sufficient to address these challenges. In a post-carbon future, existing transport infrastructures will emerge as increasingly inadequate. It is also possible that existing infrastructure owners, such as airports, many of which are fully privatized, will be reluctant to finance and accommodate the infrastructure required for future air transport operations, an especially opportune topic given recent concerns that the owners of privatized airports are ignoring government proposals to enhance operational capacity through the provision of new infrastructure, thereby limiting regional and national economic growth [2].

The research presented here is three-fold. First, it will examine the extent to which new and potentially radically different infrastructure would be required to enable the operation of commercial aircraft using alternative fuels and/or propulsion mechanisms. Second, it will provide a stakeholder analysis for infrastructure transitions in the arena of airport

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infrastructure, in addition to an overview of emerging trends and potential path trajectories, all with a view to assessing how airport owners and other critical regime players can either facilitate or hinder the transition to alternative technologies. Finally, it will speculate on transition management strategies that have the potential to circumvent short-term commercial considerations thwarting the introduction of more efficient air transport infrastructure within a reasonable timeframe. The paper thus has relevance not only to air transport, but also to other polluting industries that, at present, rely largely on petroleum-based energy or other carbon-intensive fuels.

2. Contextual remarks on the current paradigm

It is likely that air transport will be the slowest of all the major transport modes to adapt to a carbon-constrained future. The widely-anticipated advent of peak oil, as discussed by Charles et al. [1] and Moriarty and Honnery [3], will be of especial significance since the current generation of airliners rely on high-octane aviation gasoline, known as Jet-A fuel [4]. It is expected that conventional aviation fuel will become increasingly expensive, the current global market correction of oil prices notwithstanding, thereby reducing growth in the sector and marginalizing the use of air transport for anything other than low-weight/high-value items and passenger transport [5]. Furthermore, the introduction of emissions trading schemes (ETS) that include transport, and air transport in particular, are also likely to impact heavily on the sector, mainly on account of the petroleum-based fuel used to power current turbine-engined aircraft.

Airlines are widely regarded as substantial contributors to global carbon pollution and reportedly contribute 3 to 5% of global CO_2 emissions [6–8]. CO_2 emissions of aircraft are also worse than CO_2 emissions from other sources because they are emitted at higher altitudes [7]. Although the EU has not yet included air transport in its cap-and-trade ETS, it is likely to be included in the future [9]. Other proposed emission trading schemes, such as that outlined in the Carbon Pollution Reduction Scheme (CPRS) White Paper released by the Australian Government in late 2008, includes the aviation industry in the nation's forthcoming emissions trading scheme [10], now due to commence in July 2011.

One of the most significant factors contributing to the relative inability of the air transport sector to adapt to the changing transport and energy policy environment is the enormous costs involved in the research and development (R&D) activities conducted by airline and engine manufacturers, in addition to the established diarchy between Boeing and Airbus Industrie [11]. In particular, long product lifecycles and huge sunk costs are major barriers for technological change [12]. Authors often refer to the sunk costs of any major infrastructure program and the enormous financial difficulty of changing tack once substantial outlay has been made [13,14]. For example, it could potentially take Airbus Industrie roughly 20 years to make a profit on the new Airbus A380 [15]. Given that the A380's airframe is designed to be propelled by conventional turbine engines, the short-term potential for alternative technology to be used in modern airlines is limited, save for the use of aviation fuel derived from biofuels. At present, it would make little business sense for Airbus and Boeing to shift rapidly to a new technological paradigm. This is because recently launched projects such as the aforementioned A380 and the Boeing 787 Dreamliner still have a long way to go before they have paid for themselves, let alone generate an acceptable profit.

With respect to airport infrastructure, many of the same principles hold true. Conventional fixed-wing turbine-powered aircraft constitute an operating regime that impacts on the infrastructure required to operate and maintain them [16]. Considerable space is required for take-off and landing, more so when larger airliners are involved. The highly combustible nature of aviation gasoline and the inherent dangers of air transport in general also mean that airliners must take-off and land at some distance from airline terminals, thereby contributing to the airport's space demands. Aircraft design has thus played a critical role in the development of airport infrastructure [17,18]. It also results in significant negative externalities to communities (aside from the positive ones such as economic growth in the region and employment), especially with respect to noise and vibration [19]. In essence, the current air transport paradigm favours space-rich airport sites [20].

A further case illustrating the intimate connection between vehicle and infrastructure is provided by the Airbus A380. This aircraft is only slightly larger than the Boeing 747,[1] though its somewhat larger size impacts on airport handling arrangements. Terminals designed to accommodate the 747 cannot always fit the A380. Since airports rely to large extent on the landing fees charged to airlines, even though they are diversifying into non-aviation activities [21], airport owners have little choice except to augment their infrastructure accordingly. If not, airports face a loss in revenue as airlines choosing to operate the A380 take their aircraft, and their business, elsewhere. Airports incapable of handling the A380 will soon become second-tier facilities. The A380's introduction creates other problems. Although only marginally larger than the 747, the A380 has a larger wake vortex, which means that aircraft must wait longer before they can land or take-off after an A380[2] [22,23].

Air transport technology therefore has substantial consequences for airport infrastructure. Though the industry has witnessed a largely incremental progression in technology [18], such as with the Boeing 787 Dreamliner and its high proportion of light composite materials [11], larger and more powerful aircraft have necessitated significant cost with respect to upgrading airport infrastructure. The introduction of radically different air transport technologies could result in

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[1] Compared to the soon-to-be-introduced Boeing 747–800 series, the Airbus A380 is 3.4 m shorter, 11 m wider and 4.7 m higher.

[2] The affects of the larger vortex are still contested. As a precautionary measure, extra distance has been issued as safety requirement for aircraft following the A380 after landing or take-off (the distance depends on the size of the following aircraft).

even more substantial expenditure for airport owners. The role that airport owners should play in shaping air transport technology therefore emerges as highly problematic.

3. Technology transition

Transitions resulting from technological innovations can have a marked impact on the supporting infrastructures. In principal, there are two distinct types of innovation: *incremental* and *radical*. Incremental innovations are one-step improvements on an existing technology, while radical innovations imply an entirely new technology [24]. In this case, the conventional technology will, in time, be totally replaced by the new technology [12]. Radical innovations are usually also substitution innovations [25,26]. Technology, furthermore, is rarely stand-alone, but is almost always a component of a *technological system* [24]. Within this system, all components are interrelated. Changing one component will influence the institutional, regulatory and economic context of the entire system. These innovation externalities can have widespread impacts. For example, the replacement of oil with coal as a primary fuel source in some systems resulted in not only the fuel's substitution, but also a change in the distribution network [27,28]. The liquid state of oil required the creation of an oil-pipe network, thus removing some of the need to transport the fuel by boat or truck, as was the case with coal. These externalities, however, can also militate against innovation on account of the 'lock-in' effect, or the path dependency embodied in the incumbent technology [14].

It has been repeatedly demonstrated that, with the introduction of a disruptive and substituting technology, old market leaders fail to remain in their place [12,14,26]. This is because they either: (a) lack sufficient financial resources to cut their losses, thereby allowing them to overarch their sunk costs in the supplanted technological paradigm, and switch to the new technology; or (b) simply fail to change rapidly enough to keep up with the rate at which new companies using the new technology grow. By extension, new companies are free from the burden of sunk costs that could otherwise reduce profits. This allows them to overtake entrenched market leaders [14].[3]

The modern aviation industry is not characterized by rapid technological adaptation. As Moors [29] shows, systems resistant to change (usually characterized by high technological complexity and high social interactions) will hamper implementation of new technology on account of the large financial risk, the extent of technological changes required, and the uncertainty of the final advantages of implementation. This is especially true for the aviation industry [30]. In general, it takes at least one generation of new aircraft design before new technologies are fully implemented. Since a design and certification period takes approximately 10 years, while airplanes have designed service lives of around 30, it can take a new technology up to 40 years before it replaces an 'old' technology [31]. For example, GLARE, a revolutionary fibre metal laminate of aluminium and glass fibres bounded by an epoxy was patented in 1987 [32,33]. It took roughly 20 years of thorough testing and certification before it was allowed to be used in commercial aircraft.

With this low adaptation speed in mind, Allen [13] has made a prediction regarding the speed at which an alternative technology such as liquid hydrogen (LH_2) could change the current aviation paradigm, if one assumes a natural technology diffusion without the influence of external forces, such as a carbon price. Allen forecasted that LH_2-powered aircraft would take at least 90 years to reach a 50% global share [13]. Ponater et al. [34] predict a faster introduction as pressure to change increases (50 years). But, as the need for a new propulsion fuel becomes more urgent, it is likely that external forces will become more influential.

4. Alternative propulsion technologies

The next section will review some of the potential air transport technologies for energy alternatives that could have a significant impact on airport infrastructure over the next 50–100 years. The authors do not assign any weight of probability to the technologies discussed. Despite this, it is likely that air transport will continue to favour the existence of a dominant paradigm given the broader infrastructural constraints signalled previously. It is not especially likely that competition will be witnessed between two or more of the technologies discussed, as is likely to occur with road transport.

Three specific technology options will be dealt with here. The emphasis is necessarily on 'sustainability'. In the context of the aviation industry, this refers both to the existing technology's lack of environmental sustainability, in addition to the knowledge that the fuel supporting the current technology is finite. Incremental change to the existing technological paradigm will only take us so far, which means that a truly sustainable energy substitute must be renewable [35]. According to Whitelegg [36], a sustainable entity should satisfy three basic conditions:

- It can be allowed to use any sort of renewable resources at a rate not exceeding the rate of their regeneration.
- The rate of use of non-renewable resources should not exceed the rate at which sustainable renewable substitutes have been developing.
- The rate of emission of pollutants by any entity should not exceed the assimilative capacity of the environment.

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[3] Such a change is illustrated by the automobile's introduction in place of the horse-drawn carriage. The idea was to place an engine into a carriage. Carriage builders generally did not have the ability to change their production methods to steel quickly enough. Companies starting from scratch, such as Ford, adapted more quickly to the new technological paradigm and prospered accordingly.

The three options considered all have the potential to fulfil Whitelegg's basic conditions. This paper, however, does not claim that any of these will become *the* technology of the future—they are merely used as examples of plausible aviation energy alternatives.

4.1. Liquid hydrogen (LH_2)

There are two ways of using LH_2 as an aviation fuel: (i) as a direct fuel in a combustion engine; and (ii) as a means to create electricity though the use of fuel cells (covered further below).

LH_2 as a direct propulsion fuel keeps the essence of the jet turbine intact, a factor likely to improve its overall attractiveness. A LH_2-powered jet turbine emits largely water vapour rather than the greenhouse gases associated with petroleum-fuelled turbines [37,38]. LH_2 can be produced by electrolysis of water using electrical power from any renewable energy source [39]. Hydrogen can also be produced by the gasification of biomass [38,40]. A further positive characteristic is that it is lighter than standard Jet-A fuel, thereby resulting in a lower take-off weight and reducing the energy required for take-off [41].

The use of LH_2 poses considerable problems. It has less energy potential per unit size compared to conventional jet fuel. To do the same job, a 100-seat airline would need to be substantially larger, or else would need to reduce its capacity. The addition of external fuel tanks or tanks on top of the fuselage would increase drag over longer distances, thus necessitating more fuel being carried [13]. The use of LH_2 therefore necessitates a radical re-think regarding what future airliners might look like, something which could potentially impact on airport infrastructure and operations. All in all, the energy efficiency loss of LH_2 as a replacement of Jet-A fuel is predicted to be only 2% on a 3000 nm flight [41], provided that structural limitations are resolved. A further constraint is that LH_2 needs to be stored, in considerable volume, at a temperature lower then minus 253 °C (its liquefaction point) [13]. This requires vast amounts of energy [42].

Allen [13] demonstrates that major restructuring and redesigning of airports will be needed. He estimates that the installation of a cryogenic LH_2 production and storage facility at a typical airport of around 700 flights a day would require a facility occupying roughly 70 acres of land, and would need a electricity power supply of about 3.3 GW. In short, since the majority of electrical energy around the world is generated from carbon-emitting coal-fired power stations [43,44], the use of LH_2 would need to be accompanied by a massively accelerated use of renewables, or a shift to more nuclear power, with all its potential downsides [45]. LH_2 also brings with it the question of who would pay for the significant infrastructure required to keep the fuel in a viable state at the airport, and who would pay for the energy needed to keep it below minus 253 °C. This is especially important given that electricity generated from renewable energy or nuclear power is unlikely to be cheap [42].

4.2. Electricity

Electricity's use as a direct power source for propulsion is not new. Most existing systems, however, rely on an external supply of power. More recently, electric cars and bicycles have been developed and produced [46]. These vehicles make use of an internal power supply, a battery. However, owing to the low-energy density of batteries vis-à-vis the high-energy density of fossil fuels, long-range performance is problematic. For example, 1 kg of the best lithium battery has only 1% of the energy potential of 1 kg of gasoline [47,48]. This is the main reason that electricity is not generally considered a particularly likely replacement for fossil fuels, especially for aviation purposes, though it may have context-specific applications, at least until battery technology becomes sufficiently advanced.

Several experimental aircraft have recently been flown that are powered by battery-stored electricity. Some examples are an unmanned vertical-take-off-and-landing (VTOL) aircraft with hybrid turbine-electric propulsion [49] and the all-electric ElectraFlyer-C airplane, which uses a regenerative capability to top up the batteries when the aircraft encounters strong thermals [50]. NASA has experimented with a solar-powered aircraft that, in theory, can sustain flight indefinitely [51,52]. These aircraft have proved the concept of electricity as an aviation propulsion source. It is also technically possible that electricity could be used to power the compressor used on jet turbines [49]. A zero-emissions airliner, at least at point of use, would result.

There are, however, some limitations. First, one of the main requirements for sustainable electrical aircraft is the use of a renewable power sources to create electricity at the source. Second, the challenge remains to develop batteries capable of achieving higher energy densities. Third, the adaptation of electricity as a power source for aviation will trigger significant changes in the design and development of aircraft and aircraft materials, especially with respect to weight.

Another option is the use of hydrogen fuel cells. Fuel cells convert the chemical energy of hydrogen directly (electrochemically without combustion) into electricity [42]. Fuel cells, the potential of which has been demonstrated in the automobile industry [53,54], offer several theoretical advantages such as higher efficiency compared to combustion, emissions composed of water rather than noxious gases and a reduction in rotating equipment, thereby reducing noise and vibration [42]. In the aviation industry, fuel cells have been positively tested on an unmanned aerial vehicle [55] and a small airplane [8,56]. The main restrictions are the creation and storage of hydrogen, as related above.

4.3. Biofuels

Biofuels are usually defined as a solid, liquid or gaseous fuel derived from relatively recently dead biological material [39,40]. Biofuels are seen as a very promising renewable energy source. Since most current transportation vehicles use

Table 1
Summary of available options and impacts.

Impacts on	LH_2	Electricity	Biofuels
Fuel creation	• Need for availability of sustainable energy. • Plants will require large space.	• Need for availability of sustainable energy. • Different sources have different impacts.	• Fuel creation will most likely remain with oil companies.
Fuel transport	• New infrastructure required for transportation.	• Current infrastructure will need to be upgraded to allow heavier usage.	• Fuel transport will largely remain the same though some upgrades will be needed.
Fuel storage/ provision	• Existing fuel stations will need to be upgraded. • Large amounts of energy required for fuel storage.	• Electricity cannot be stored practically. • Provision will remain similar.	• As a 'drop-in' fuel, storage and provision will remain the same, though some upgrades might be needed.
Aircraft design	• Upgrading/refitting required for existing aircraft. • New design of aircraft needed in the future.	• New design of aircraft needed. • New light materials and new concepts expected.	• Minimal impact on aircraft design.
Engine design	• Small adaptations to current jet engines. • New design needed for future engines.	• Basic electric engine principal will probably remain the same.	• Minimal impact on engine design.
Airport planning	• Fuel creation and storage would be best close to the airport to minimize costs. • Will require large space and thus different airport planning.	• Less impact on provision infrastructure. • New plane concepts can lead to different airport planning, i.e., longer runways.	• Minimal impact on airport planning.

internal combustion engines requiring liquid fuels, biofuel substitution would require the least amount of change in technology and infrastructure.

There are generally considered to be four 'generations' of biofuel. The first generation produces fuel from starch, sugar, vegetable oil and animal fat [20,57]. The problems with first-generation biofuels range from net energy losses to greenhouse emissions to increased food prices, in addition to deforestation and increased use of pesticides and herbicides in biomass cultivation, with ramifications for the surrounding environment [39,40].

Second generation biofuels are a more viable solution since they use waste biomass and agricultural residue such as corn stalks, in addition to dedicated biofuel crops [20] and jatropha [58]. By using specially designed microorganisms, the feedstock's tough cellulose is broken down into sugar and then fermented. Alternatively, a thermo-chemical route can be taken, whereby biomass is gasified and then liquefied in a process known as 'biomass-to-liquid' [59]. The use of waste biomass and dedicated, easy-to-grow feedstocks has a considerably lower environmental impact compared to first-generation biofuel production [20].

Rather than improving the fuel-making process, the third generation uses improved feedstocks. Designing oilier crops, for example, could greatly boost yield [40]. Scientists have designed poplar trees with lower lignin content to make them easier to process, while researchers have already mapped the genomes of sorghum and corn, which may allow genetic agronomists to modify the genes controlling oil production [60]. Another possible source is algae, which can produce 30 times more energy per square meter compared to land crops [61], though the process to extract the algal oil has not yet been perfected [62].

A fourth-generation technology combines genetically optimized feedstocks designed to capture large amounts of carbon with genomically synthesized microbes created to make fuels [63]. The key is the capture and sequestration of CO_2, a process which theoretically ensures that fourth-generation biofuels are a *carbon negative* source of fuel [64]. However, the weak link is a lack of adequate carbon capture and sequestration technology.

Biofuels seem to have captured the greatest amount of attention within the aviation industry. Their impressive qualities remain a powerful argument for their use, especially in light of the minimal infrastructural changes required, as would have to occur with LH_2 and, to lesser extent, electric flight. Biofuel is thus seen as a 'drop-in' fuel requiring minimal adaptation to the current generation of jet engines. In late 2008 and early 2009, two successful independent test flights were conducted by Air New Zealand and Continental Airlines, both using aviation turbine fuel[4] derived from third-generation biofuel [65,66]. Later analysis of the test flights also showed fuel savings compared to Jet-A fuel, e.g., 1.2% on long-haul flights and 1% over shorter ranges [67].

There are, however, several difficulties to overcome. Biofuels currently have a limited shelf life of about 6 months and, what is more, decrease the lifetime of elastomeric sealing in the fuel system [41]. In addition, it has a higher solidification point than Jet-A fuel, which means that it solidifies at normal aircraft operating conditions of around −20 °C [41]. Biofuel thus needs to be 'upgraded' into Jet-A grade fuel before it can be used in jet turbines, a highly energy-intensive process [1]. To summarize, all three options discussed have hurdles to overcome, as shown in Table 1.

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[4] Air New Zealand used a 50/50 jatropha/Jet-A blend, while Continental Airlines used an algae/jatropha blend. One engine ran on a 25/25/50 algae/jatropha/Jet-A fuel blend, while a second ran on a 50/50 algae/jatropha blend. For both tests, no modifications were made to the engine(s). More importantly, no difference in performance was reported.

All the paradigms investigated largely depend on the availability of sustainable electrical energy in some form. LH_2 requires significant amounts of energy for its creation and storage. Electrical aircraft require direct energy to charge its batteries on the ground, and/or will need regenerative options while in flight. Biofuels need to be converted into Jet-A grade fuel before they can be used in conventional turbine engines. With regard to infrastructure changes, a switch to a LH_2 will have the largest impact since a completely new infrastructure would be required. The electric propulsion option will make use of existing infrastructure that will need to be upgraded. Biofuels, however, can largely rely on existing infrastructure. Though these three options currently stand out as the most promising fossil fuel substitutions, others are being researched. The aviation industry and its various stakeholders have not yet collectively chosen a sustainability ‘champion’ since the technologies explored here have yet to overcome all obstacles required for widespread sustainable implementation. Biofuels come closest, at least in the short term.

5. Existing regime players

Several theories and themes exist in stakeholder analysis. For the sake of coherence, the major themes identified by Laplume et al. [68] will be used. In accord with their theory, the main stakeholders in the current airport infrastructure paradigm will be identified, and their main interests and influence described. This stakeholder analysis will be performed using the ‘Airport Corporation’ as the centre point in the aviation industry network. In accord with de Haan [30] and Amaeshi and Crane [69], the most important stakeholders are the airport owner(s), airplane manufacturers, engine manufacturers, airplane operators (i.e., airlines, freight companies, etc.), the government (at various levels), and the community, both in the near vicinity of the airport and in the broader region.

The next step is to position the stakeholders in the network and identify their objectives, as well as to assess the most important threats and how their potential impacts can be defined. Here, an effort is undertaken to (i) develop an understanding of the stakeholders’ interests, and (ii) make a prediction regarding the likely strategies that they will employ to influence the decision-making process [68]. Combining these insights can provide an indication of how stakeholders will react to different situations. This rationale is then applied to the problem under investigation. A short description regarding possible stakeholder reactions towards more sustainable aircraft propulsion is given after each stakeholder description.

5.1. Airport operators

In general, airport operators have invested large sums of money in existing infrastructure, which is closely aligned to the requirements of current airplanes optimized for using Jet-A fuel [30].

Since airports are largely dependent on airlines making use of their facilities, there is a formal relationship between the airports and the airlines, usually in the form of a contract whereby airlines rent slots and space [16,21]. When airlines decide to use new types of airplane, airports can decide to modify airport infrastructure as required, if they feel that doing so it will ultimately benefit them. This occurred with the introduction of the Boeing 747 and the A380, which resulted in airstrips having to be elongated and terminals having to be adapted [70]. However, since these infrastructural changes require substantial investments, airports will obviously not make these decisions lightly.

Privatized airports are driven by profit maximization. Their goal is to optimize the utilization of available space and utilities. To generate revenue, airports will try to attract not only airlines to their airport, but also investors, retailers and other businesses so as to increase their non-aeronautical revenue input [21]. A potentially debilitating factor is the huge sunk costs inherent in airport infrastructure. Economic downturns, or changes in technology, can therefore heavily impact the airports’ economic viability, and their ability to recoup investments [16]. Another threat is the frustration of proposed developments by governments or community stakeholders.

The introduction of a new technology requiring new or enhanced infrastructure would not be especially welcomed by the airports. This is because they would either have to change the current infrastructure completely or, if the technology was introduced gradually, would be forced to operate two different infrastructures simultaneously. Both options could prove very costly. Substituting the current fuel supply with biofuels would require fewer significant changes with respect to the current paradigm [71]. In this case, the airport would be able to retain most of its existing infrastructure and still gain a return on current investments. The use of biofuels would thus be likely to gain support from the airports, especially vis-à-vis LH_2. On the other hand, if a hydrogen paradigm found support in the car industry, for example, the required infrastructural costs could be reduced. In this case, a larger non-airport-specific energy paradigm would be underway, something which would make LH_2 more acceptable.

5.2. Airlines

The airlines have large sunk costs invested in their main assets, i.e., their aircraft (aside from airlines leasing aircraft). These assets are acquired from manufacturers offering a range of airplanes. Depending on the airports to which they fly, and the routes serviced, airlines will choose airplanes that best fit their specific operational needs. Once in a while, the choice of airplane, such as the A380, requires adaptation on the part of the airport before it can be used optimally. If an airport is unwilling to upgrade its facilities, this could lead to either the airline leaving the airport, or the airline purchasing another, more conventional, aircraft.

With the introduction of radical technological innovation, airlines will initially be reluctant to upgrade their fleets. The large costs involved in selling old airplanes, which would have a markedly reduced salvage cost, and acquiring new ones could prove a large burden for airlines, many of which operate with only very marginal profits, if indeed they do record a profit. Most likely, the introduction of a radical technology will lead, as predicted by innovation theory [12,24], to the rise of new airlines.

For these reasons, it is postulated that airlines, in a similar way to the airports and airplane manufacturers, would favour incremental technological change. The substitution of biofuel for fossil fuel is therefore more likely to be supported than a radical technological change, such as switching to LH_2, or even electrical aircraft. However, long-term factors such as emissions trading and green taxes might change the position of the airlines.

5.3. Airplane manufacturers

Airplane manufacturers invest large amounts of resources in the development of new aircraft. As seen with the A380, it can take decades before the manufacturer starts to make a profit [15]. This makes the manufacturers dependent on their main clients: the airline operators and leasing companies. It is in the manufacturers' best interest to keep airlines satisfied and meet market demands. This, however, is partly a gamble, since it is difficult to predict what kind of aircraft will be needed in 10–20 years, when the latest design becomes operational, or over the period of time during which the manufacturers intend that R&D costs will be recouped [30].

A transition from Jet-A fuel to a new propulsion method, such as LH_2, would mean that current airplanes would have to be refitted. In time, completely new aircraft will have to be designed to optimize the new technology, as discussed earlier. This would entail a large loss with respect to investments already made [13]. Such radical technological change is unlikely to be overtly supported, and is even less likely to be embraced by current airplane manufacturers, at least without justification. This stands in contrast to more incremental technological change, such as the substitution of fossil fuel by biofuels. As a result of lower costs associated with minimal infrastructural changes, such a transition is likely to gain support from the industry.

5.4. Community

The community affected by the airport can be divided into two groups. These are the community closest to the airport, and therefore the group most directly affected by technological change, and the community surrounding the airport up to a 20 km radius [72]. Both groups will have concerns about environmental issues, economic and land-use interests, and safety. In particular, the community would like air travel to have the least possible environment impact. The economic impact of an airport is also of great importance, especially given the close association with airport growth and economic development [73,74]. Safety issues are paramount since the closer community fears the possibility of air crashes. As seen with several incidents, air crashes can have a great impact on communities around an airport, witness the 1992 crash of El Al flight 1862 in the Bijlmermeer in Amsterdam [75].[5]

In addition to these general concerns, the community closer to the airport will have concerns about noise and emission levels. This is because these externalities negatively impact on health and reduce the value of property [76]. With the introduction of a new technology, the most significant concerns from the community will be, in the first instance, safety and noise [69]. Any new technology that increases risk, emissions and noise levels will be unwelcomed. At the same time, technology that has the potential to reduce these factors would be applauded.

Airline passengers, in general, are mostly concerned about travel time and cost, in addition to airport accessibility. Passengers are also concerned about safety. With the introduction of a new technology, passengers will naturally prefer the same or higher levels of safety. One of the most significant threats to any new technology is accidents and their impact on public opinion. For example, a major disaster with a hydrogen fuelled aircraft could immediately destroy public confidence in LH_2 technology [77].

5.5. Government

Government in general has an ambivalent attitude towards airports. Airports are primarily regarded as important assets for national and international mobility as part of the broader transport infrastructure network. At the same time, airports are also the source of several externalities, both positive and negative. The largest positive externality of the airport is its influence as an economic driver for the region(s) around the airport [78,79]. On the other hand, local communities also have to deal with the negative externalities such as pollution, noise, the threat of possible accidents and decreasing land values as a result of these considerations. Governments are usually charged with the responsibility of facilitating an adequate balance of these externalities.

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[5] The El Al crash resulted in the death of 43 local people, the destruction of two large apartment buildings, and the contamination of the soil in the impact area.

6. The transition arena

To determine the kinds of airport-based infrastructure that might be required to support a more sustainable aviation paradigm in both the medium and long term, three different technologies that could replace fossil fuel within the aviation industry have been examined. In addition, an in-depth stakeholder examination has delineated the boundaries of what might well be termed the *aviation transition arena* [28,78]. The following section will identify the external factors that influence the aviation transition arena. Identifying these external factors makes it possible to model a set of explorative future scenarios for the aviation arena [80]. This done, the scenarios allow us to establish preferred transition management strategies by making both the positive and negative possibilities more readily visible to policy makers, and indeed the full gamut of potential stakeholders.

As Genus and Coles [81] show, transitions usually commence when (i) prevailing socio-technical regimes start to display significant problems, or (ii) significantly better innovations are established. In our case, it is argued that, by facing a significant problem, viz., the future depletion of oil reserves and a carbon price, transition will occur. Following Geels and Schot's [82] definitions of transition paths, this case is identified as *reconfiguration*, whereby system changes occur in many technologies and organizational arrangements.

The transition arena represents a space wherein actors balance, in a process-oriented network, coherence between uncertainty and complexity [28]. The purpose of interaction within the transition arena is not so much the realization of a pre-set goal (in this case, a specific path for transition), but to develop a context for collective action as well as the instruments to enable this [83,84]. Verbong et al. [85] have identified a range of costly failures such as hype cycles, changing visions and policy priorities, all of which limit learning capabilities. The same authors outline some of the typical patterns that should be circumvented in future collaborative exercises and policy making so as to avoid limiting the learning capacity of transition players. Some of these patterns are *high expectations* and *backlash*, whereby initial promises early in the trajectory are too high and disappointment ensues. This is closely linked to *expectation successions*. Here, disappointments in other technologies positively influence the expectations of other technologies. One solution to suppress this pattern is for policy makers to not bend to credibility pressures too early during the transition process. Another pattern recurring in the same authors' research is supply-side-oriented innovation networks and narrow, closed networks. It is evident that technology networks that are narrowly supply-side oriented lead to technology-push, thereby neglecting outsiders and demands from the market [85].

In our case, the transition arena contains four main actors, these being the airplane manufacturers, the airports and airlines, the government (in its various tiers), and the community. As stipulated in network theory, actors are not confined to a single arena and are hence displayed as boundary-crossing actors [86]. For the sake of simplicity, some actors have been grouped together.

All *airplane manufacturers*, including the engine manufacturers, are regarded as one group [87]. The airplane manufacturers will be responsible for the design of the aircraft. This group can be influenced by other actors within the arena. But, if cooperation remains low, airplane manufacturers might choose their own preferred technology, thereby forcing this choice upon the industry. The second group identified is the *airlines and airports*, which are taken together. These two actors will respond similarly when faced with a new technology, as introduced by the airplane manufacturers, under the assumption that manufacturers introduce broadly feasible innovations. As seen with the introduction of the Boeing 747 and the A380, the airlines, when they purchase new airliners, undertake to retrain pilots, while airports have to upgrade their facilities. Though these two actor groups have a symbiotic relationship, the airlines and airports can be characterized as followers. Indeed, while both can influence the direction of the transition, they will ultimately depend on what the manufacturers offer. The third actor group is *government*. Although three tiers of government were identified in the stakeholder analysis, this model aggregates the three dimensions, which are collectively seen as responsible for legislation and accompanying regulations associated with air transport and planning decisions. *Community* represents the final group and consists of all third-parties involved with the airport, including passengers and people living within the airport region. Within the transition arena, these four collective groups can be regarded as the most important actors. They can choose to work together to achieve higher goals, or they can choose to remain independent and only respond to the actions of the other actors.

The transition arena itself is influenced by two main external factors. These are (i) the perceived need to change the aviation industry towards a more sustainable aviation paradigm (henceforth, the perceived need), and (ii) technological innovation. These external factors require some explanation. The perceived need is a direct result of a global perception of the environment and is influenced by society as a whole. Geels and Raven [88] call this 'socio-cognitive evolution'. Perceptions of society as a whole are a direct result of context and the outcomes of action. Society evolves through action, interaction and experience within its ever-changing environment [88]. This leads to a perception regarding which actions are required in the future. This understanding of the past and the future directly influences the identified actors and forces them to think about a more sustainable aviation paradigm. This external factor's level of intensity will vary over time depending on consensus among society and other external factors, e.g., the global economy, security threats, climate concerns, etc.

The second external factor, viz., technological innovation, is the more immediate and tangible driver of action since it directly influences the industry's technological development. As Geels and Raven [88] show, technological innovation is a Lamarckian evolutionary process whereby technology evolves through the discarding and retention of various incremental

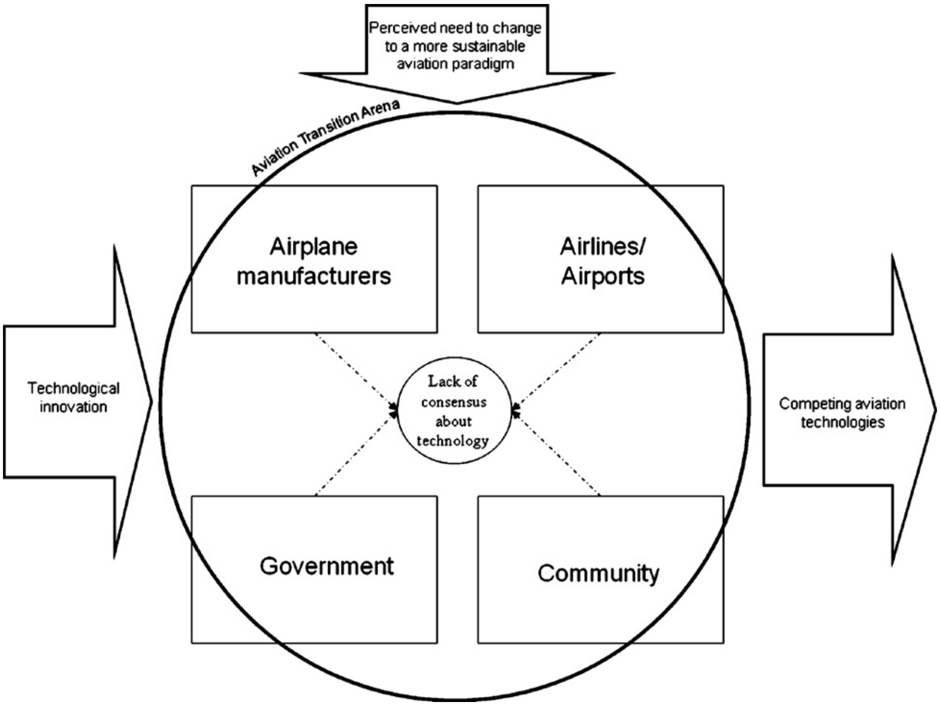

Fig. 1. The aviation transition arena: no consensus.

technologies. In this sense, technological innovation is not merely a push from innovators, but is also influenced by society, since society as a whole influences which innovations should be retained or discarded. Technological innovation is therefore influenced by the actors in the transition arena *and by* research and development (R&D). These different influences on technological innovation are represented in Fig. 1, where all actors of the aviation transition arena individually influence technological innovation.

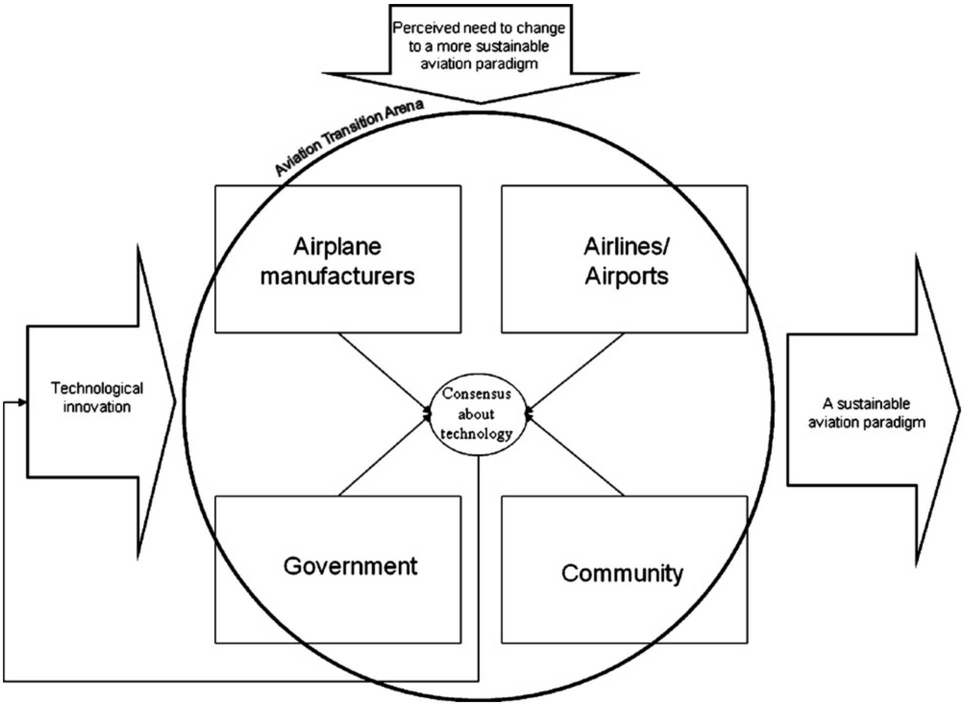

Fig. 2. The aviation transition arena: reaching consensus.

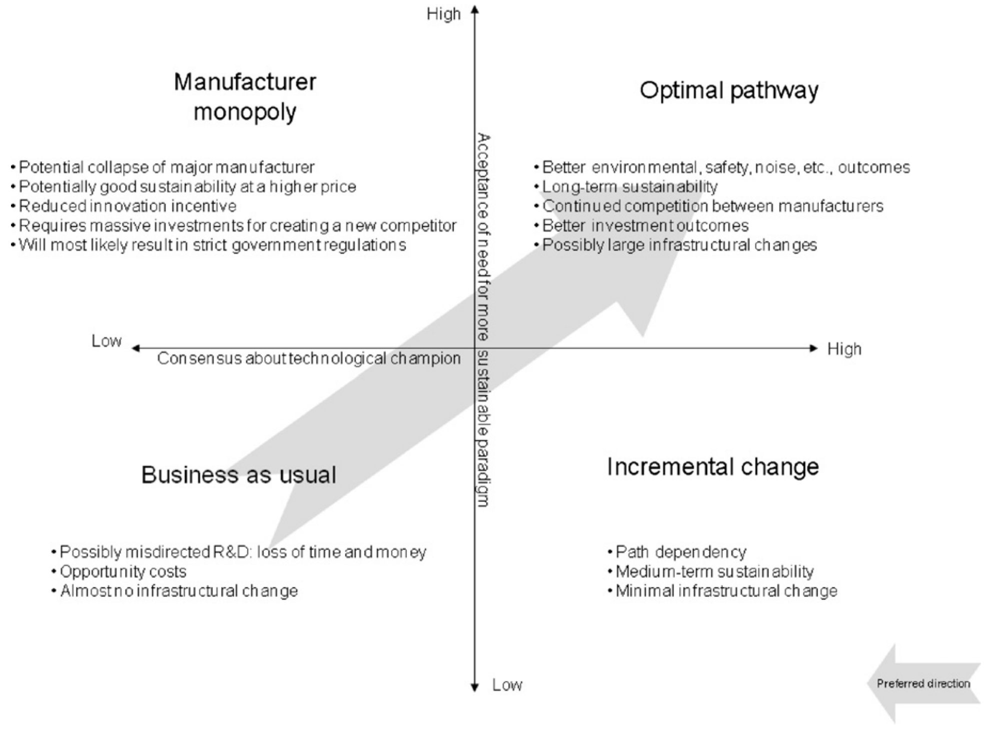

Fig. 3. An overview of scenarios based on the *perceived need for change* and *consensus about technology*.

One way of increasing useful output in the transition arena is by breaking this traditional process for technological innovation [82,85,88,89]. To do so, the actors in the transition arena need to reach a consensus on a single goal. The level of consensus reached between actors directly influences the likelihood of reaching a desired end-goal [86]. This is represented in Fig. 2, where the actors reach a consensus on technology and thus influence technology together, as opposed to individually. It follows that, the higher the level of consensus reached, the more likely it will be that a desired goal can be reached with fewer resources [87]. Reaching a consensus within the aviation transition arena is therefore one of the most important outcomes of the required network process.

The two external factors identified above are represented in a diagram above (Fig. 3). As related earlier in this article, these external factors are used to present future scenarios for the commercial aviation paradigm. Both factors make up the axis of the diagram. The present situation represents lowest scores on both factors. When either of the two factors increases, the industry will move towards one of the other quadrants. These quadrants thus illustrate explorative future scenarios, the importance of which is clearly signalled by Carlsson-Kanyama et al. [80] in the context of future planning.

7. The scenarios

The scenarios as presented in Fig. 3 above are technological scenarios describing what could happen to the aviation industry if certain pathways are taken, based on the sustainable technology overview and the stakeholder analysis presented earlier. Societal factors within these scenarios are represented within the external factors influencing the direction of the pathway, not the scenarios themselves. The intention, here, is to show the potential technological trajectories and their effect on the aviation industry.

7.1. Business as usual: low consensus and low perceived need

Industry will adhere, in general terms, to the current pace of technological change. Investments will be hedged, and multiple technologies will continue to be researched. Although this is not necessarily a bad thing, it does mean that it is more likely that significant financial resources will be misallocated to pursuing technologies that will not become commercially feasible. This money could have been better invested in other aspects of the business, or accelerating the development of the most promising technology (the result of a missing consensus).

Most likely, business as usual will not lead to large infrastructural changes, unless a serendipitous technological breakthrough that is economically feasible occurs. In this scenario, considered to represent the base line, the current infrastructural form is very likely to remain more or less the same over the medium term.

7.2. Manufacturer monopoly: low consensus and high perceived need

When the industry perceives a high need for sustainable change, yet fails to reach a consensus on technology, different actors within the transition arena will invest their resources in different 'champions'. There is an inherent danger attached to this strategy, since only a very small number of major airplane manufacturers are currently active. If all manufacturers invest in different technologies, there is a threat that one technology will turn out to be the best, which will leave the rest as losers. This could lead to the losers' demise since they might not have enough capital left, on account of the small margins endemic in the industry, to switch to the same technology as the winner, or catch up with the market lead established by the winner.

Though this scenario might reach a more desirable level of sustainability, it is likely to come at higher cost. If a monopoly ensued, there would also be an increased need for government interference, such as regulating the remaining monopolist. A monopolistic market could also lead to a mere incremental increase in environmental performance after the initial market break-though, since market incentives for radical change would be markedly reduced. A monopoly market would also set a very high barrier for new players to enter. Massive investments, at cost to the taxpayer, would be required to level the playing field. This scenario's effect on airport infrastructure is difficult to predict, since the path's outcome could potentially relate to any environmental performance improvement.

7.3. Incremental change: low perceived need and high consensus

The third scenario is where the industry will reach a consensus, yet the perceived need remains low. If the industry places all its bets on one single technological path, it is likely that this technology will be in the industry's short-term best interests, such as allaying stakeholder concerns and satisfying shareholder requirements. This would probably result in the implementation of a technology of medium sustainability, so as to please government and the community, yet it would also be one requiring a minimal amount of infrastructural changes.

A path dependency with mediocre sustainability credentials might be the best option in terms of monetary resources over the short to medium term, but could prove undesirable in the long term since a more substantial transition will potentially be needed at a future point. This could result in greater overall cost regarding the transition from an unsustainable aviation energy source to a more genuinely sustainable one, and thus represents a misallocation of resources.

7.4. Optimal pathway: high consensus and high perceived need

If the industry reached a high level of consensus under the influence of a highly perceived need, this could be considered the optimal pathway to greater sustainability. The optimal pathway is where the long-term sustainability of a technology is reached, which would lead to better environmental conditions, higher levels of safety, and less noise, etc. With a high perceived need, it is easier to free more resources to research and develop sustainable solutions. In conjunction with a negotiated consensus on technology established within the transition area, this joint effort could lead to a fast and robust transition in aviation technology, in addition to a more economical allocation of resources from a long-term perspective.

If all players within the arena had access to the same technology, competition between the main manufacturers will remain. It will, however, be likely that this scenario will lead to significant infrastructural changes, the costs of which would have to be carried by all players within the transition arena.

8. Conclusion

As the need for sustainable solutions increases over time, alternative technologies will gain more attention. Some of these technologies have a potentially high degree of viability. Recent tests with biofuels in an aviation context, in addition to hydrogen fuel cells in the automotive industry, show that these technologies are on the brink of breaking through to market, though when exactly this will happen, and how quickly, is difficult to predict. It is important for the aviation industry, and airports in particular, to understand what impact technological transition will have on existing infrastructural systems. The aviation industry has always relied on the presence of oil as its main fuel source, and a clear path dependency is in effect. The substitution of aviation energy from petroleum to another source will have a severe impact on the current supporting technology. A new energy paradigm may require a new distribution network, a new way of generating the fuel, a new type of engine, and perhaps even a new design of aircraft. It is quite possible that an unmentioned (or hitherto un-invented) technology could become the new world standard. No matter which technology gains the upper hand, the aviation industry, and its stakeholders by extension, must be ready to adapt to this technology and provide the requisite infrastructure. With the current global economic climate, it is understandable that investing money in possible future technology will not be high on the list of priorities for airports, though it cannot be ignored indefinitely.

This paper had set out to show to what extent more sustainable technologies could impact on the existing infrastructure. It has investigated three potentially viable propulsion options that have the capacity to provide a more sustainable outlook for aviation, provided that some important conditions pertaining to stationary energy provision are met. A short summary of these impacts has been given in Table 1. It is clear, however, that major paradigm shifts cannot sufficiently be supported by airports alone, especially with respect to potential modifications to the infrastructural systems that currently support commercial aviation. The aviation industry, as a whole, will need to be responsible for ascertaining the best way forward.

This can only be achieved by coordinating the efforts of the various stakeholders in an established aviation arena. The coordination of this arena needs to be established before the actual implementation of any technology. Indeed, when implementation begins, the appropriate networks and instruments should already be established. To achieve the facilitation of any transition, it is suggested that the actors engage in a process-oriented interaction with a view to establishing the appropriate networks and instruments. Again, this process-oriented interaction is aimed at enhancing coordination by establishing the appropriate context, and balancing the uncertainty and complexity of the identified factors; in this case, 'the perceived need for change' and 'consensus about technology'. The review of technology given here in this paper, in addition to the review of possible scenarios, can be considered a preliminary tool to establish this context.

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