Detecting Future Potentials for Step-change Innovation in Aeronautics – Progress and Challenges

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ABSTRACT

Prospective overall concepts for aeronautics require a fundamental understanding of future technology options, their physical boundaries and technical challenges. For this reason, Bauhaus Luftfahrt (BHL) has established the "technology radar" based on future technology analysis in the domains of energy, materials, photonics, sensors and information. It acts as an antenna for the early detection of innovation potentials and brings design-driving and disruptive developments from all disciplines into the focus of aviation. In this contribution, we present progress and challenges of future technology analysis in general and in particular of the proprietary processes at BHL. Using example cases, such as substitution of fossil by renewable electric energy, and relevance and mitigation potentials of cosmic radiation exposure in future aviation, we demonstrate the value of the four cornerstones of the above-mentioned "future technology analysis" methodology and comment on derived application potentials for aeronautics.

KEYWORDS: *electric aircraft, electro-fuel, radiation shielding, hydrogen, hypersonic flight*

NOMENCLATURE

AIRCAT - Assessment of the Impact of Radically Climate-Friendly Aviation Technologies
bpd - barrels per day
FTA - future technology analysis
GHG - greenhouse gas
GtL - Gas-to-Liquid
ICRP - International Commission on Radiological Protection
LAPCAT - Long-Term Advanced Propulsion Concepts and Technologies (EU project)
LH_2 - liquid (cryogenic) hydrogen
NCRP - National Council on Radiation Protection and Measurements
PtL - Power-to-Liquid
StL - Sunlight-to-Liquid
Φ – geographic latitude

1 INTRODUCTION

1.1 The need for future technology analysis

"More than anything else, technology creates our world" writes W. B. Arthur in his book on "The Nature of Technology" and adds that "it creates our wealth, our economy, our very way of being" [1]. In fact, F. P. Boer says in his book on risk-adjusted "Valuation of Technology" that the "creation of wealth through technological innovation is one of the most important economic phenomena of the modern world", yet "technological innovation is a notoriously risky and competitive business" [2]. Obviously, innovation leaders with very long product life-cycles require long-term foresight capabilities to successfully navigate this risky territory. It is our mission at Bauhaus Luftfahrt to research long-term future mobility solutions in order to provide best-possible future-proof guidance in the "fog" of the unknown world of 2035 and beyond. Innovation leaders, policy makers and the public in general require this foresight in order to make informed decisions within the constraints of the inherent uncertainty in the nature of science, innovation and futurist foresight.
A high priority therefore is future technology scouting, analysis and monitoring. How can we identify future technologies, determine their future innovation potentials, and do this holistically for a long-term time scale? Here we present an approach that works for a wide scope of technologies from component

level to integrated system level. This paper presents progress and challenges of future technology analysis in general and in particular of the gained knowledge of continuous conducted proprietary processes.

1.2 Structure and outline

The paper is organized as follows:
Section 2 presents the challenges and context in which the methodology for future technology analysis (FTA) is developed. The challenge is to practice a scientific futurist approach instead of prediction, in the same sense that e.g. past history is subject to high-standard of scientific research. The challenge is also to understand the relevance of scientific and technological advancements, and their combinatorial possibilities outside the classical aviation disciplines. The context of FTA is also defined by the two forces of "push" and "pull". Breakthrough achievements in science, in technology development and in combinatorial innovation ("push") as well as ambitious long-term targets for aviation ("pull") require future technology analysis.
Section 3 outlines the four cornerstones of Bauhaus Luftfahrt's approach to FTA. Section 4 illustrates selected aspects of FTA using two example cases, the long-term perspectives of introducing renewable electric energy into the aviation system, and relevance and mitigation potentials of cosmic radiation exposure in future aviation. We demonstrate the value of the four cornerstones of BHL's "future technology analysis" methodology and comment on derived application potentials for aeronautics. The final Section 5 concludes the paper with a summary.

2 CHALLENGE AND CONTEXT OF FUTURE TECHNOLOGY ANALYSIS

2.1 Future performance potentials versus future performance prediction

Anticipating the future is a key element of strategic decision-making, of securing competitive advantage and of circum-navigating potential threats. However, the notion of correctly anticipating the future, especially step-change innovation or long-term perspectives, from present knowledge is an illusion. Before presenting progress and challenges of future technology analysis in aeronautics, we accept two seemingly contrasting notions, firstly, that of fundamental unpredictability of the future and secondly, that of sufficiently robust insights into the long-term future resulting from in-depth analysis instead of prediction, forecast or trend extrapolation.

The first notion of unpredictability accepts that there exist no "hidden indicators" that accurately predict step-change and/or long-term forecasts. The illusion of predictability may have several roots. For example, Moore's Law of 1959 was based on Gordon Moore's observation at that time [3] and had no proof of long-term future technology potentials when formulated. It was an educated guess based on technology history and extrapolation rather than the resultof a technology analysis of the long-term future. Still it is viewed by some as a reliable method of predicting future trends and is used for the semiconductor industry's strategic roadmap [3], thus having attributes of a self-fulfilling prophecy. However, mechanisms of indeterminism in complex or in strongly coupled systems such as modelled by W. B. Arthur showed that technological development and returns in the economy including random events, amplified by positive feedback through increasing economic returns, leads to a probabilistic selection of the outcome over time [1]. There is abundant proof of the impossibility and failure to predict the future.

The second notion says that there are scientifically sound approaches that produce useful cognition about the long-term future, that provide guidance in strategic decision-making. Leaving aside impossible prediction, there are indeed several other types of possible and useful approaches to "future management", e.g. by researching future possibilities and potentials [4]. Rather than asking which solution comes at what time in the future, which tries to elicit predictions, we must ask, what is the (physical, technical, operational, economic etc.) potential or performance limit of a set of solutions incorporating the selected technology in a distant future. Although combinatorial innovation brings about radical discontinuities that nobody could have anticipated [1], we believe that possibilities and potentials for such discontinuities can be assessed: this type of insight about the future can be derived on a scientifically sound basis [5,6]. This type of approach is presented in this paper.

Future performance potentials and/or innovation potentials represent the quantitative limits of performance by which a set of technology solutions is bound and give valuable insight. The next step is to identify the driving technology factors that exploit this performance potential. These driving factors provide guidance in the resource allocation to find promising solutions. In short, resource allocation decisions need first the knowledge of ultimate performance potentials before any particular solution involving a novel technology is developed. The "envelope" function of how far a technology solution can improve things -when fully developed- provides guidance in setting priorities for further research and development. Experience in future technology analysis shows that in the process sometimes unanticipated innovation perspectives emerge, as application case 2 in this paper presents (see .4.2)

2.2 Prerequisite for detecting future potentials for step-change innovation

There are several prerequisites to identifying significant developments that have the potential for step-change innovation [6], which are an

1. interdisciplinary team of experts who understand the relevance (for aviation) of breakthrough results in both basic science as well as in technological innovation outside the field of aviation,
2. combinatorial creativity and
3. intelligent analysis capability with a "future technology analysis" methodology.

Novel technologies may be the product of breakthrough results in "use-inspired basic science" [7] but there are other complementary origins of innovation as well. Looking deeper into the history of technological evolution, we find examples of radical innovation by a novel combination of existing technologies, or by transferring existing technologies into a new context. This is obviously true for electric Tesla cars initially being powered by laptop (mobile computing) batteries. Recent examples are electric personal air vehicles still showing the phenotype inherited from electric multi-copter drones. The first-ever production of Sunlight-to-Liquid aviation fuel [8] points at a future radical innovation potential drawing from both breakthrough science (redox reactant material and reactor design) [9,10] and a combinatorial innovation in system technology (heliostat concentrators originally used for power plants, redox reactor for syngas production and Fischer-Tropsch reactor for fuel production) [11].
In order to detect future potentials for step-change innovation in aviation, we have to look outside the classical aviation disciplines. "The change in vision" proposed by W. Brian Arthur is to shift "from seeing technologies as stand-alone objects each with a fixed purpose, to seeing them as objects that can be formed into endless new combinations" [1]. Such combinatorial vision of step-change innovation is definitely true for the fast-evolving and mere endless combinatorial possibilities in the digital age.

2.3 Technology push-pull context

Future technologies are analyzed from a push and pull perspective. The technology push originates e.g. from advances in science and technology that may have innovation potential in aviation. Technology pull is caused by "drivers of change", opportunities and threats, such as climate change, urbanization, and digital transformation. Examples of both technology push and pull in aviation are listed in Table 1.

Technology pull arises e.g. from ambitious long-term targets for aviation that are formulated in Flightpath 2050 [12] and the roadmap documented in the Strategic Research and Innovation Agenda [13] and IATA [17]. Furthermore, there are global, European or national strategies in the domains of energy, materials, transportation, environment, information and communication technologies etc. In its early years, Bauhaus Luftfahrt identified and quantified technology pull in the topics of travel time reduction, airport capacity, electric and hybrid-electric flight, alternative energies and fuels, efficient propulsion, aerodynamic efficiency by in-flight morphing, and process and data management for aircraft design, later followed by e.g. cosmic radiation shielding, high-temperature materials, structural health monitoring, airborne broadband communication, data analytics and Artificial Intelligence (AI) support for aircraft design, manufacturing and operations. At the same time, the FTA approach has been used to identify promising technologies that push into the solution space.

Technology push arises e.g. from significant advancements in technologies such as future high-C-rate batteries, non-biogenic fuel production via Sun-to-Liquid (StL), Power-to-Liquid (PtL), graphene and nanotechnology in lightweight composite materials, additive manufacturing, broadband free-space laser communication technology, Nobel-award-winning optical comb frequency-stabilization and blue laser diodes, quantum technologies, and cyber-physical systems, to name a few. A selection is listed in Table 1 below.

Table 1: Push/pull representation: The push created from a selection of potentially disruptive technologies, and the pull originating from ambitious targets that call for radical rather than evolutionary innovation

Energy and fuel technologies	
Push	Power-to-Liquid [14] and Sunlight-to-Liquid [15] aviation fuel technologies
	High-C-rate (charge/discharge) electrical energy storage >5 kW/kg [16]
Pull	Global fleet 50% Green House Gas (GHG) emission reduction in 2050 relative to 2005 [17]
	New aircraft 75% CO_2 emission reduction in 2050 relative to 2000 [12,13]
	High-capacity electrical energy storage towards 1 kWh/kg [18]
Material and structure technologies	
Push	Boron-nitride nanotube composites [19-21] (see also Section 4.2)
	Graphene (R&I funded with 1 billion € by the EU Graphene Flagship Project [22])
Pull	Multifunctional lightweight materials, radiation shielding materials
	Adaptive (morphing) lightweight materials
Information, communication and sensor technologies	
Push	Cyber-physical systems (e.g. Internet of Things, ubiqitous sensors)
	European high-performance IT infrastructure (EU Cloud Initiative, ~ 2 billion € [23])
Pull	Integration of air transport and data networks and services
	Autonomous, intelligent & evolving systems

3 THE BAUHAUS LUFTFAHRT APPROACH TO FUTURE TECHNOLOGY ANALYSIS

The in-house approach to future technology analysis relies on an analytical methodology especially developed to guarantee a quantitative, reproducible and transparent assessment of innovation potentials. Its four cornerstones are:

1. Derivation of (universal) **metrics** (performance indicators, criteria, technology functions) and figures of merit to identify step-change improvements and enable the comparison of fundamentally different technologies.
2. **Benchmarking**, i.e. the derivation of performance reference values such as physical limits (e.g. Carnot efficiency) or technical targets, expressed in terms of the developed metrics to gain knowledge on what the potential performance benefit of a novel technology is.
3. Analysis of the **scaling** behavior to quantify the adaptability of an emerging technology, e.g. to the volume, size, or power requirements of the potential application. This gives insight into whether the technology may be implemented on a large scale with the same degree of efficiency or performance as on the laboratory scale.
4. **Disruptive potential** analysis, i.e. a quantification of a technology's potential to radically improve the economic or technical performance of a product, service or business model and to thereby lead to a discontinuous change.

Metrics or performance indicators and their reference values (benchmarks) need to be carefully chosen to be useful. It is common practice to take the state of the art as reference, and the results show a potential for improvement over the state of the art. We find it in most situations more useful to take the best-possible performance under idealized conditions as a benchmark for reference. This creates an envelope function in the sense of an innovation potential. If this is sufficiently promising, then particular technologies are evaluated and compared against this potential as a frame of reference.

These choices need expert knowledge because of a dilemma in achieving either objectivity and "future-proofness" or system-level decision support by (economic, utilitarian, ecological) "valuation" of technology. Physical indicators such as conversion efficiencies, energy and power densities yield rather future-proof results but need to be interpreted at system level. System-level figures of merit on the other hand, such as direct operating cost or cost-competitiveness, life-cycle GHG emission or socio-economic impact are very useful for decision support but include assumptions on many unknown quantities and are therefore less future-proof. It is therefore important that the derivation of performance is traceable to these assumptions. Traceability allows to perform parametric studies that show the Pareto envelope, the robustness of results and the dominating "driving" performance parameters.

The in-house approach to future technology analysis was applied to determine performance potentials in the aeronautical context at various levels of complexity, from components, devices, to integrated systems, covering "physical" technologies as well as "cyber-physical" and information technologies for digital transformation. This approach led, for instance, to the early detection of future potential for step-change innovation in de-carbonization of aviation: prime examples are the BHL analyses for electric flying [18,24,25] and for non-biogenic solar fuels [26]. The methodology led to the detection of novel technical synergy potentials for sustainable flying at low cosmic radiation levels emerging for nanocomposites as new structural material [19,20] and for hydrogen as a fuel [19,27,28]

4 APPLICATION CASES

To illustrate elements of the FTA approach, we selected two key drivers, firstly, climate change mitigation and secondly, travel time reduction, and match them with selected aspects of technology analyses for decarbonizing aviation and for cross-polar as well as high-altitude hypersonic flight.

4.1 Application case 1: Decarbonizing aviation with renewable electric energy

The transformation of the energy base from fossil to renewable energy is one of the most important challenges for the aviation industry's long-term future [26]. This creates a pull for alternative fuel technologies and for electrification of aviation [25].
In the long-term future, the largest resource and the largest part of harvested renewable energy will be in the form of electrical energy [29], either from direct solar-to-electrical conversion, wind or water energy resources (although with regionally varying characteristics of sustainable scalability, supply stability and cost). Therefore, various ways of decarbonizing aviation with renewable electric energy are of particular interest.

4.1.1 Fully electric aircraft

Battery-electric flight came into the focus of future technology analysis at Bauhaus Luftfahrt in 2008, triggered by news of several scientific breakthroughs pushing the limits of battery performance. One such breakthrough was the development of nanowire silicon anodes that could reversibly expand and absorb large amounts of lithium ions with a step-change improvement in battery anode capacity [30]. At the same time, nano-coatings on certain electrode materials enhanced ion mobility and enabled extremely high power densities. The progress of electro-mobility at a macroscopic level seemed to be partly determined by progress of ion and electron mobility in the nano-world. This observation brought nanotechnology into the focus of detecting future step-change improvements in electrifying aviation.

On component level, two key performance indicators for FTA are the specific energy (energy-mass ratio) and specific power (power-mass ratio). For a useful comparison of batteries with kerosene and hydrogen, we must take the specific "useful energy" (i.e. "exergy") as a metric, not the (total) specific energy, and the relevant component or sub-system mass. This appreciates the fact that a fuel heating value has less exergy than energy content (Second Law of Thermodynamics and technical limitations) and that a battery is an integrated energy storage and electric power delivery device, corresponding to the system boundaries of a package of kerosene with turbo engine and generator or, e.g., the combination of hydrogen with a fuel cell. Alternatively, one may compare shaft power, taking the system boundaries of a battery with electric engine for comparison to kerosene with turbo-engine.
The specific energy of kerosene is 50-60 times higher than for batteries but the more appropriate specific exergy is only approximately a factor of 25 apart. This is an important insight if we take kerosene as a reference (benchmark) value. Future technology analysis takes results from single

electrode and cell research to determine the specific exergy values of a standard cell and its future potential [25], which is to achieve specific exergies beyond 500 to up to 800 Wh/kg. The rapid increase of specific energies for lithium batteries by an average rate of 7 % year-over-year between 1994 and 2010 is an interesting observation but extrapolation of this trend in the sense of a Moore's law for specific energy of batteries has no scientific basis, in contrast to our performance potential analysis.

At an integrated system level the evaluation of the performance indicators such as propulsive power, mass, block energy and aircraft efficiency, and their benchmarking with conventional turbo-engine systems requires modelling of optimized electric transmission cable and propulsor, design and sizing of the structural weight (growth factors), aerodynamics of integration etc. Therefore, the choice of metrics and benchmarks at higher integrated level requires cross-disciplinary competence. Significant disruptive potential in battery-operated 190-PAX transport aircraft over a 900-nm range was determined to require batteries on the order of 1.5 to 2 kWh/kg, while specific power of 1.2 kW/kg for take-off is within the performance envelope of batteries today. [18]

At an integrated global air transport system level, a key performance metric is the "CO_2 savings potential on global fleet level in 2050", with the expected fuel consumption by aviation in 2050 or in 2005 as a reference [31]. The Bauhaus Luftfahrt Ce-Liner study [18] of a fully electric aircraft with entry into service in 2035 and conservative production ramp-up assumptions showed a 3-4% CO_2 savings potential on global fleet emissions in 2050 [32,34]. The study was presented in the context of the recent "Assessment of the Impact of Radically Climate-Friendly Aviation Technologies" (AIRCAT) Workshop where an evaluation by another group based on rather optimistic assumptions of production ramp-up yielded a 12-15% CO_2 savings potential [33]. These results show that, compared to the radical progress a single fully electric aircraft represents with potentially more than 80% CO_2 savings compared to conventional aircraft, the global impact on CO_2 savings is severely limited to few percent. The reason is limited production capability, fleet growth and renewal, i.e. the relatively small number of such novel aircraft entering into operation compared to the number of conventional aircraft remaining in service. The same is true for any radical aircraft innovation, be it the introduction of fuel-cell powered aircraft using renewable hydrogen or other technology using non-drop-in fuels that cannot be retrofitted. However, if we evaluate direct operating cost in the global fleet, the performance metrics must capture aspects such as cost of electric energy and battery life, impact on local emissions (NO_x, particulate matter and noise) and corresponding airport fees, which could also enter a future analysis on CO_2 abatement cost.

In conclusion, even with step-change reduction of emissions by such radical aircraft innovation, the climate mitigation impact towards 2050 is very limited [34]. The battery is a more than adequate source of power but a very limited source energy to go the distance [35]. Therefore, today we experience two developments, firstly a strong "push" for short missions down to 30 min, driving the development of all-electric ultra-short reach personal air vehicles, and intensive research towards hybrid-electric architectures which offer a combinatorial variety of new solutions, typical for combinatorial innovation. For operating the air transport system on renewable electricity, technologies other than fully or hybrid electric motive power systems need to be considered as well.

4.1.2 Electro-fuels

An alternative path is the introduction of electrical energy in aviation via "drop-in" or "non-drop-in" electro-fuels for internal combustion engines or for fuel cells: the production of "electro-fuels" such as Power-to-Liquid (PtL) synthetic paraffinic kerosene, methane, alcohols or hydrogen. These technology options come with widely differing characteristics, to be investigated along the four cornerstones of FTA. Key performance indicators are energy conversion efficiency, land use or area-specific yield, water demand, production potential, production cost and competitiveness, specific life-cycle (well-to-wake) GHG emissions, and potential impact on global GHG emission reduction. Their definition is well developed along with their benchmark values which also have been used in multiple-criteria assessment frameworks for evaluating different paths to drop-in fuels [14,36].
There is an obvious "physical" disadvantage to overall efficiency of using electro-fuels for mobility in general. Converting electricity, which is 100% exergy, to a fuel, the heating value of which is then used to create "useful" motive power is a chain of inefficient processes – but technically speaking, for aviation

this efficiency penalty is over-compensated by the benefit of the high on-board specific energy (and exergy) of liquid hydrocarbon fuel. The extent to which these fuels will enter the aviation system strongly depends on the economic viability. This metric needs to assume a fixed spot price of fossil kerosene as a practical reference value, with the disadvantage of price volatility now and in the future.

The third cornerstone of FTA, the scaling property, is of particular interest: key performance indicators such as fuel production cost may scale favorably with plant size and cumulative production capability, due to economy-of-scale effects and learning curve effects, respectively. However, the sustainability and production potential of feedstocks, and associated cost of procurement are possible limiting effects in the net GHG emission reduction potential. This metric is linked to the specific carbon intensity of the fuel and to the scale of the production volume to satisfy the future demand of the global fleet.

At an integrated global air transport system level, the performance metrics are the CO_2 savings potential on global fleet level in 2050. Drop-in capable electro-fuels (PtL) in form of paraffinic kerosene can be introduced to the entire fleet, and can decarbonize the entire fleet with no modifications to airport infrastructure or aircraft fuel systems. Therefore, the limitations of introducing this innovation by fleet renewal and growth do not apply. Yet, the ramp-up of production capability still applies, firstly, to the feedstock renewable CO_2 from air capture (in the long term at large scale), secondly, to the provision of renewable electricity, and thirdly to the fuel production plant.
The scaling problem arises from the estimated 450-500% increase in fuel demand in 2050 compared to 2005 [31,33,34]. To reach the IATA target of 50% reduction of GHG emission in 2050 compared to 2005 approximately 90% of the CO_2 emissions (compared to conventional Jet A) need to be removed. Most renewable fuel technologies do not satisfy this condition. Power-to-Liquid (PtL) and Sunlight-to-Liquid (StL) fuels have the potential for such low values if precaution is taken to use purely renewable CO_2 and renewable primary energy [14,15], and are technically scalable to the growing demand. Even with an extremely low carbon intensity of 10%, i.e. 90% less than fossil kerosene, a 100% substitution of the estimated 570 Mt/a of fossil kerosene in 2050 would be required in order to reach the IATA target of 50% reduction relative to 2005.

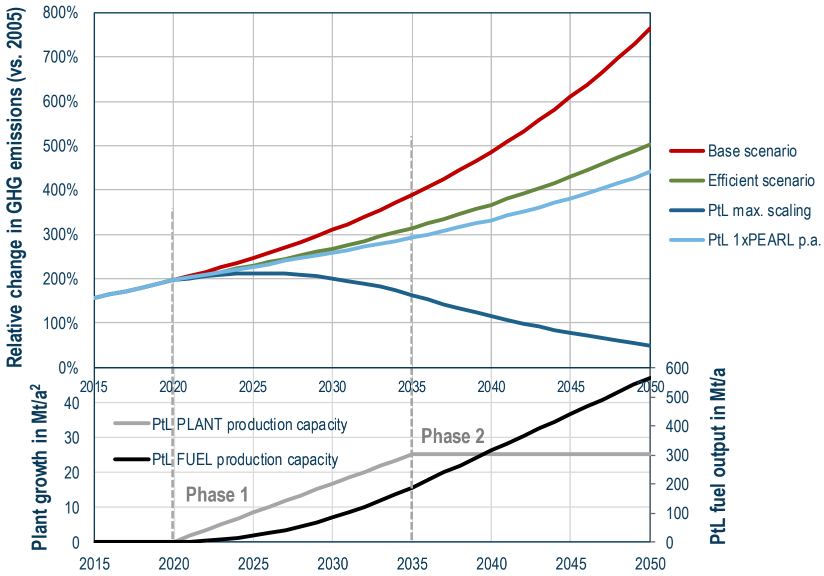

Figure 1: PtL fuel production volume and its impact on the global fleet GHG emission; in phase 1 production capacitiy for PtL plants is developed from zero in 2020 to a maximum value in 2035. In phase 2, PtL plants are produced at maximum rate. If that maximum rate corresponds to one PEARL-size plant deployed per year, then only 12.5% GHG emission savings are achieved in 2050. The extreme case of maximum scaling to 25.2 Mt/a^2 for 100% substitution of Jet A (570 Mt/a fuel output in 2050) yields a 50% emission reduction in 2050 relative to 2005.

In order to calculate the CO_2 savings potential on global fleet level we assume for simplicity that scaling solely depends on the ramp-up function of fuel production with 10% carbon intensity (90% reduction for substituted fossil kerosene). We assume that the production capability for PtL plants develops in two phases:

- In phase 1, the short- and medium-term 2020-2035 time frame, linear growth of PtL plant production capability
- In phase 2, the long-term 2035-2050 time frame, constant maximum PtL plant production capability

The linear ramp-up of production capacity for PtL plants (measured in Mt/a^2), by integration over time, leads to quadratic increase in cumulative fuel production capacity (measured in Mt/a). This ramp-up-phase is assumed to start in 2020 and to reach its full PtL plant production capacity in 2035. In phase 2 from 2035 to 2050 the constant production capacity for PtL plants at this maximum value leads to a linear growth of PtL fuel production capacity.

We consider two cases: (a) the necessary scaling of production capability to reach the IATA goal in 2050 with PtL fuel alone, and (b) the CO_2 savings potential on global fleet level in 2050 if the maximum production capability for PtL plants is equivalent to the deployment of one PEARL-size Gas-to-Liquid (GtL) plant (see below) per year, including the plants for CO_2 air capture and the required renewable electricity production.

a) Scaling of PtL production capability for 100% substitution of Jet A by 2050

In order to reach a 100% substitution of 570 Mt/a Jet A by 2050, the annual production of PtL plants needs to rise from zero in 2020 to 25.2 Mt/a^2 in 2035, and to remain at this level to 2050. This leads to a quadratic growth of PtL fuel production capability from zero in 2020 to 190 Mt/a in 2035, followed by a linear growth to 570 Mt/a in 2050, assuming all plants are kept in operation until 2050 (no retirement of plants). The deployment rate of PtL fuel production capability of 25.2 Mt/a^2 translates into adding each year a PtL kerosene production capability of 538 000 bpd.

For comparison, the large GtL plant "PEARL" in Qatar (development cost around 20 billion Euro) has a production capability of 140 000 bpd liquid hydrocarbon fuel (gas-to-liquids products containing kerosene). If we assume that future Fischer-Tropsch plants produce with one liter jet fuel also 0.87 liter naphta, then a PEARL-size plant would deliver 74 900 bpd (3.50 Mt/a) jet fuel. The required deployment rate of PtL plant capacity is then equivalent to 7.2 times the PEARL plant per year. The investment cost would be far higher than 7.2 times the PEARL reference, because the production capacity for renewable CO_2 and renewable electricity has to be installed as well.

b) Scaling of PtL production capability equivalent to one PEARL-size plant per year

Assuming a maximum deployment rate of PtL plant capacity equivalent to one PEARL plant per year (in phase 2, 2035-2050), the annual production of PtL plants rises in from zero in 2020 to 3.50 Mt/a^2 in 2035 (in phase 1), and remains at this level to 2050 (in phase 2). This leads to a quadratic growth of PtL fuel production capability to 26.4 Mt/a in 2035, then to a linear growth to 79.2 Mt/a in 2050, an approximate PtL fuel production capability equivalent to 22.6 PEARL-size plants. With this capacity, 14% of conventional fuel can be substituted. Assuming a carbon intensity of 10% relative to conventional jet fuel, this fraction leads to a CO_2 savings potential of 12.5% on global fleet level in the long-term perspective of 2050, equivalent to a factor of 4.4 emission increase compared to 2005.

This result shows the "size" of the challenge the IATA goals present and how important a scaling assessment is for the evaluation of these novel fuel technologies in the global fleet context.

In summary, the future technology analysis of introducing renewable electric energy into the air transport system covers the entire scope from nanotechnology to emission impact at the global fleet level. Although electro-fuels are technically capable of decarbonizing air transport by 90% by 2050 (equivalent to the IATA goal of reducing to a 50% level in 2050 compared to 2005), the practical issues such as economic viability and market mechanisms as well as scaling limitations due to cost and availability of capital are likely to limit the impact. It will be interesting to compare the effort for the three strategies (PtL, hydrogen and (hybrid-) electric aircraft) of reaching a reduction target sin 2050, i.e., to include hydrogen-operated aircraft as a third alternative. For quantification of the effort one should evaluate indicators such as the overall required investments (infrastructure, supply, aircraft development, manufacturing and operations), direct operating cost (including airport fees for local emissions) as well as a "CO_2 abatement cost" function in aviation, which is beyond the scope of this paper.

4.2 Application case 2: Cosmic radiation shielding – relevance and technical synergy potentials

Since 2011, BHL confronts future trends in air traffic with the associated increase in cosmic radiation exposure and analyzes technical synergy potentials for its mitigation [19,20,27,28]. In the following, the identified associated aviation drivers of change, their implications in terms of radiation exposure as well as significant co-benefits of future technologies for radiation shielding will be presented based on the BHL approach to future technology analysis (cf. Section 3).

4.2.1 Technology pull in response to future trends in cruising altitudes and polar route frequencies

Travel time reduction is a key driver for air traffic development. As an example, it has leds to the ever-increasing number of cross-polar flights from a couple of hundreds at the turn of the millennium to more than 15,000 today. Compared to conventional routes requiring gas stops, besides flight time reduction and direct intercontinental connections, cross-polar routes allow for benefits with regards to fuel burn, associated environmental emissions and climate impact due to contrail formation [37].

Useful metrics for measuring the relevance of cross-polar flights rely on the associated Revenue Passenger Kilometers (RPK) and include in particular their growth rate and their relation to the corresponding ones for all intercontinental flights. While by now the average RPK of cross-polar flights makes up a couple of percent of that of all intercontinental flights, we find the associated average RPK growth rate to be with impressive 26% per year almost 6 times larger than for intercontinental flights. This continuing trend mirrors the rapid growth of Asian markets (with economic growth rate of 4.1% per year, outpacing the global average by 2.9 % [38]), which drives economic bonding with North America and boosts the demand for polar routes in comparison to other segments of air traffic.
Furthermore, driven by a significant potential for travel-time reduction, future high-altitude, high speed air transportation concepts are being explored with cruise speeds (substantially) exceeding that of the supersonic airliner Concorde operating until 2003. For instance, by means of hypersonic flight, direct connections over the largest intercontinental distances could be realized within a few hours of travel time (cf. Figure 2) [39].

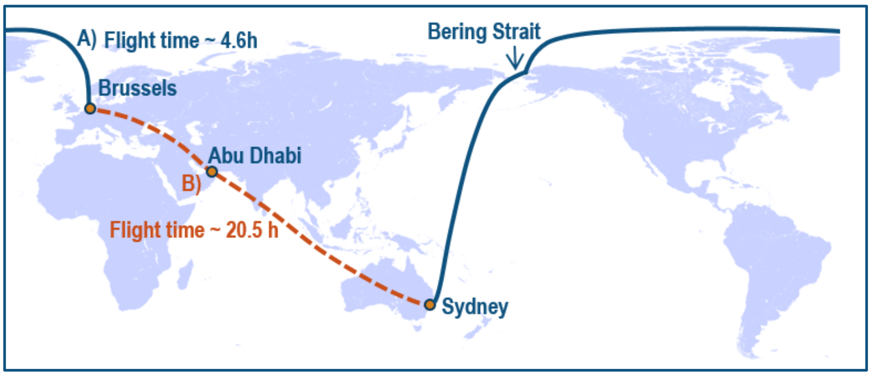

Figure 2: Representative flight trajectories for the baseline mission Brussels to Sydney of the EU-funded LAPCAT study [39] for a route with A) hypersonic cruise (at Mach 5) and B) the conventional subsonic reference.

From the confrontation of the above-mentioned on-going trends in polar route frequencies and flight altitudes with the associated risks due to cosmic radiation for aircrews, frequent flyers and avionics, Bauhaus Luftfahrt has derived a technology pull with regards to the mitigation of potential radiation exposure in future air traffic.
It stems from the fact that owing to the composition of the Earth's atmosphere and its magnetic field, up to 20-25 kilometres above ground, radiation intensities strongly grow and are maximal at the poles

[27,28,40]. Accordingly, compared with trajectories at lower latitudes, transpolar flights are generally subject to a higher effective dose rate, which serve as a metric for the biological response to ionizing radiation.

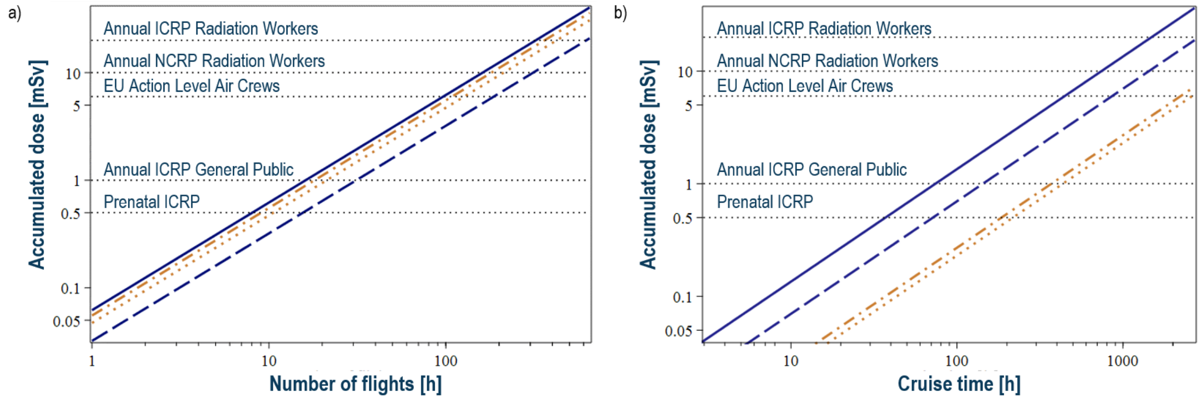

Figure 3: Accumulated dose on the trajectories A) and B) (cf. Figure 2) during solar minimum (solid and dot-dashed) and solar maximum (dashed and dotted) for a) increasing flight number and b) increasing flight hours together with the recommended annual radiation limits.

As an instructive means to evaluate the relevance of cosmic radiation in air traffic, we have calculated the dependence of the annual effective dose on the number of flights as well as on cruise time for representative subsonic and hypersonic missions for solar maximum and minimum, respectively corresponding to the two periods with respectively lowest/highest time-averaged radiation intensities in the sun's 11-year activity cycle. Selected results are plotted in Figure 3 together with various recommended annual dose limits for aircrews (classified as radiation workers) as well as for the general public [41-43]. For instance, for the general public as well as radiation workers these annual limits correspond to the equivalent of respectively about 10 and up to 200 chest-x-rays [40].

While elevated cruise speeds go along with higher flight altitudes and typically with transpolar routes, at least for passengers, the resulting higher dose rates may (partially) be traded by shorter flight and hence irradiation times, which is in particular the case during solar maximum (cf. Figure 3a)). One furthermore observes that in periods of solar minimum on the hypersonic and subsonic trajectories A) and B), allowable limits for the general public would already be surpassed by about one return-flight every 1.5 months (or correspondingly respectively 8 and 9 return-flights per year). Triggering of EU action levels for aircrews as well as excess of the recommended NCRP annual limits for radiation workers would respectively happen for about 48 and 80 return-flights per year. Yet, during solar minimum, this only corresponds to respectively 500 and 700 flight hours on trajectory A), after which the exposures on trajectory B) would still be a factor of 3 and 5 lower (cf. Figure 3b)) and thus would not be considered as critical[1]. Hence, in general, for aircrews with fixed block hours, flying at higher altitudes implies an increase in annual dose, where the maximal exposure results for cruising speeds of about Mach 5 [28].

As concerns route-planning and aviation decision-making, economical penalties may in particular be caused by solar storms, when the associated solar particle events, i.e. sizeable fluxes of energetic charged particles, hit the Earth's atmosphere. While they occur at random, the frequency of aviation-relevant events varies between one every two months to one every two years with durations between a few hours up to maximum ten days with order of magnitude increased dose rates [45]. During these periods, hypersonic routes may not be served. The reason is that as opposed to subsonic airliners, re-routing to lower latitudes and altitudes in response to temporarily increased radiation levels tends to be difficult [27,28].

[1] Note that the subsonic trajectory B) proceeds at moderate latitudes and hence is subject to dose rates up to a factor of four lower than on a subsonic polar route, e.g. from Brussels to Beijing, for which recommended annual limits would be exceeded for a lower number of flight hours.

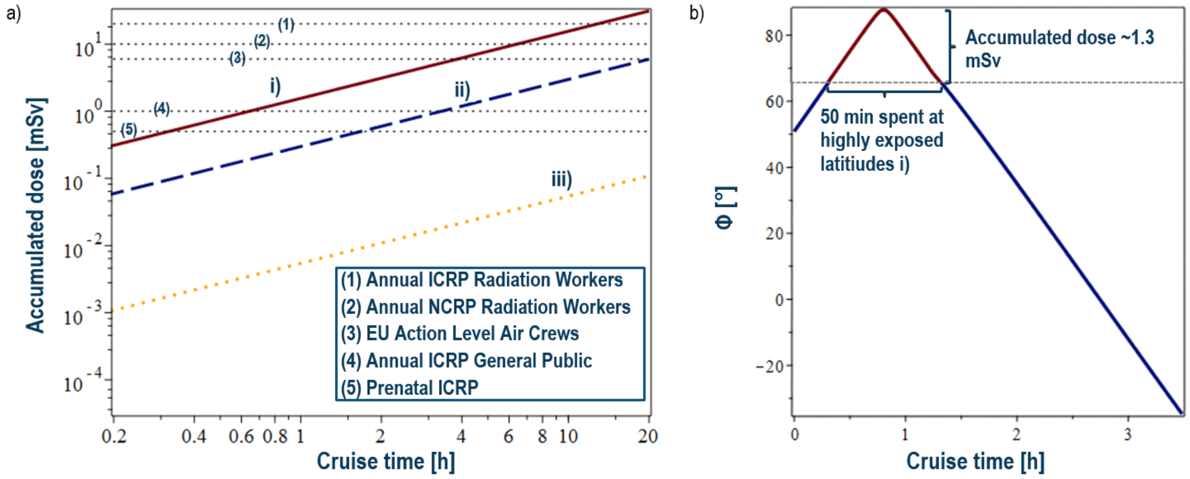

Figure 4: a) Accumulated effective dose as a function of flight time during a severe solar storm (based on event-averaged radiation rates from NASA data [40,44] for the solar particle event 3 from October 29th-October 31st 2003) calculated at 25 km altitude at different latitudes respectively for western/eastern hemisphere i) Φ≥ (55°-65°)[2]/(65°-75°)[1] (solid) ii) Φ≈(40°-50°)[1]/(50°-60°)[1] (dashed) and iii) Φ≈ (30°-40°)[1]/(40°-50°)[1] (dotted) compared with various radiation limits; b) geographic latitude as a function of cruise time for the baseline hypersonic mission Brussels to Sydney on route a) (cf. Figure 2) at cruise altitude and speed of respectively 25 km and Mach 5. As indicated, already the contribution of the 50-min-route segment with latitudes Φ≥ 65° would lead to an accumulated effective dose of 1.3 mSv, which exceeds the allowable annual limit for the general public by 30%.

As demonstrated by Figure 4a), during a solar storm, the effective radiation dose strongly grows with geographic latitude and allowable annual limits for the general public may easily be surpassed after less than an hour of flight in the polar region (cf. also Figure 4b)).
Current research goes into the exploration of space weather indicators or precursors that may be used for reliable and timely prediction of solar storm events and their extends e.g. for real-time immediacy warning of airlines and for aviation decision-making [40,44,46,47].

In summary, fostered by future trends in polar route frequencies and cruising altitudes, synergy potentials for flying economically above and beyond Earth's natural radiation protection are in demand.

4.2.2 Technology push: identifying technical synergy potentials for radiation shielding

Effective shielding of crew or radiation workers and electronic equipment from directly and indirectly ionizing radiation provides an important challenge in various domains, including aerospace and aeronautics, medicine, nuclear power installations and accelerator facilities. The conceptual design of protection supplies against cosmic radiation for airborne applications is particularly demanding. While in this case radiation spectra extend up to very high energies, yet, lightweight material solutions with high shielding effectiveness are required. In particular, at current aircraft altitudes and up to about 25 km above ground the dominant hazard to humans and aircraft electronics emerges from cosmic neutrons [48].

[2] Depending on longitude and on period within solar storm event

Highly energetic, very fast neutrons could be efficiently attenuated by radiation shielding concepts involving material components that firstly guarantee an efficient slow-down and energy loss of the incident neutrons and secondly exhibit high performance in low-energy-neutron absorption – both at minimal weight penalty [19].

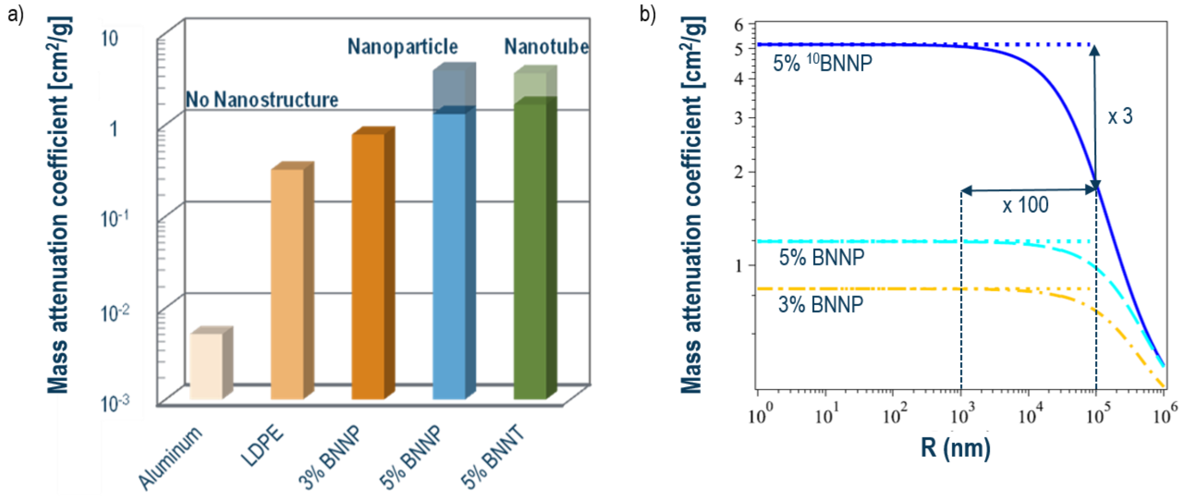

Figure 5: a) Mass attenuation coefficient as a metric for the effectiveness of low-energy-neutron shielding in relation to the mass penalty a) for Low-Density Polyethylene (LDPE), low-loading Boron Nitride Nanoparticle (BNNP) and Boron Nitride Nanotube (BNNT)/polymide composites as well as aluminium as a benchmark; b) for polymide composites as a function of filler particle size with varying loadings and elemental compositions (including boron nitride with isotopically enriched boron (^{10}BN) (solid)).

Key identified science and technology developments ("push") allowing for significant improvement in radiation shielding technology possibly in combination with enhanced structural integrity result from a) novel, specifically tailored, lightweight polymeric nanocomposite materials [19,20]. Moreover, b) valuable synergy potentials for radiation shielding were found to naturally emerge from alternative propellant options for future aviation and particularly for hypersonic systems [19]. Both options may be considered separately or be combined in order to optimize shielding performance. Insights and application potentials derived from future technology analysis are presented in the following.

a) Nanocomposites – step-change improvements in radiation shielding efficiency
Nanocomposite materials, e.g. composed of a lightweight polymeric matrix and nanoscale inclusions such as particles, nanotubes or platlets, are under intense research, since a variety of exceptional physical or chemical properties emerges as soon as at least one of the characteristic dimensions of the fillers (length/width/thickness) falls in the range of 1 to 100 billionth of a meter. This may have a geometric origin (e.g. exceptionally large surface-to-volume ratio of nanostructures or large aspect ratio e.g. of nanotubes) or be due to wave-mechanical effects gaining in importance at scales close to the quantum realm ([20] and references therein). By this means, step-change improvements for instance in mechanical properties, but also in the radiation shielding ability or both (in the sense of multi-purpose material design) may be achieved compared with conventional engineering materials. For example, nanocomposits comprising boron-containing nanostructures enable efficient neutron shielding (particularly for low neutron energies) with much less volume and weight than other benchmark materials ([20] and references therein). For instance, compared with aluminum, they exhibit a two orders-of-magnitude higher mass attenuation coefficient, which can be defined as a metric for shielding performance in relation to the mass penalty (cf. Figure 5a)). As was demonstrated by one of the authors in Ref.[20], polymer composites with neutron absorbing inclusions essentially reach the physical benchmark for optimized shielding at minimal weight penalty as soon as the filler size drops within the nanometer range (cf. Figure 5b)). This complies with the physical intuition that a uniform distribution of neutron absorbing atoms throughout the composite material (best case for shielding) is achieved more efficiently by dispersing neutron absorbing nanostructures in the composite instead of e.g. larger

microstructures conventionally used. As indicated in Figure 5b), for instance, the shielding of a 5% ^{10}BN / polymer composite increases by a factor of 3, when the radius of the fillers is reduced from 100 µm (= 10^5 nm) by at least a factor 100 to nanometer-scale < 1 µm (< 10^3 nm).

While such nanomaterials are currently investigated for applications in industries other than aviation (e.g. in aerospace or for terrestrial applications), in principle, boron-containing nanocomposites could easily by applied for instance to (parts of) the ceiling of the aircraft cabin or the cockpit in the form of a thin film, paste or foam. We verified that order-of-millimeters thin layers would lead to efficient (low-energy-)neutron absorption [19].

In order to effectively reduce the weight penalty of such a shielding solution, multifunctional application besides radiation protection – including the use for structural integrity – is conceivable. For instance, boron-nitride nanotubes embedded in a polymer matrix were shown to exhibit excellent neutron and UV shielding ability, transparency, and extremely high strength at minimal weight penalty [21].

b) Significant co-benefits of alternative fuel technologies for cosmic radiation shielding
Driven by emission as well as travel time reduction targets, alternative propellants for future aviation and for hypersonic systems are under investigation, such as for instance liquid hydrogen (LH_2) (cf. [39,49,50] and references therein). Associated challenges emerge amongst others from the required storage volume (four times larger than kerosene for the same energy content), which tends to increase the wetted area of the aircraft. Yet, the attenuation efficiency of highly energetic cosmic neutrons increases with both the dimensions and hydrogen content of the shielding assembly. Accordingly, comparing for instance conventional jet fuel with the same energy content as liquid hydrogen, a four times higher shielding volume with about 34% higher hydrogen content is at disposal for effectively reducing the energy/slowing-down highly energetic neutrons by means of elastic collisions with hydrogen nuclei (protons) [19].

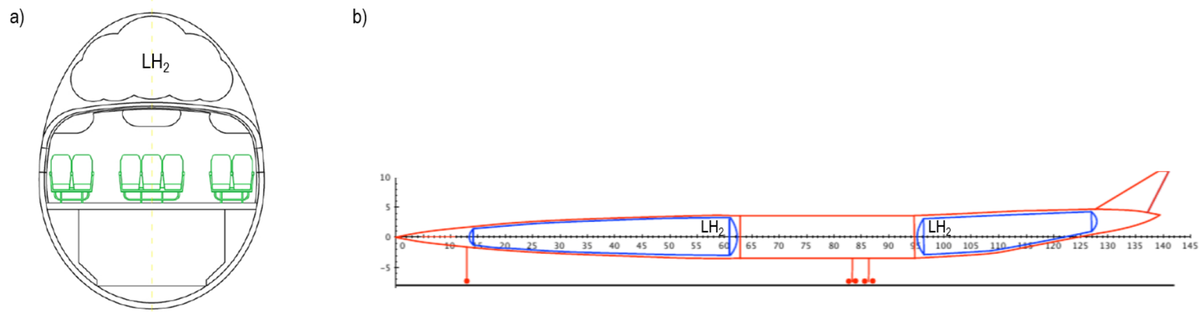

Figure 6: Considered configurations for the storage of LH_2 a) cross-sectional view of the cabin with tanks on top of the passenger cabin [49] and b) in front and behind of the passenger cabin [50].

For the determination of the dose reduction potential by means of liquid hydrogen stored in tanks, the following models/simulations are required:

1) Tank layout and position (e.g. on top or left and right of the passenger cabin, cf. Figure 6)
2) Atmospheric neutron fluence depending on neutron energy and angle as well as on altitude/latitude and on solar conditions
3) Energy loss in tanks as a function of neutron energy and incident angle that may be converted to effective neutron dose reduction as a function of position in the aircraft
4) Fractional contribution of the neutron dose to the total cosmic radiation dose at the desired altitude/latitude in dependence on solar conditions

In Table 2, we have summarized our results assuming simplified representations as well as realistic dimensions of tank layouts considered in the literature (cf. Refs. [49,50] and references therein) (a) cryoplane technology with tanks on top of a substantial fraction of the fuselage and (b) LAPCAT A2 hypersonic technology with extended tanks left and right of the passenger cabin (cf. Figure 6) for various solar conditions.

Table 2: Case-study-based reduction of the effective dose resulting from the propagation of neutrons through the LH_2 tanks (for details of the analysis cf. [19,51])

Aircraft configuration	Altitude/ Latitude	Solar conditions	Maximal neutron dose reduction	Neutron contri-bution to total dose	Best-shielded position
a) Cryoplane	10 km/ high northern latitudes	Solar maximum	48%	~50-60%	Center of aircraft (passenger cabin)
		Solar storm	63%	~80-90%	
b) LAPCAT A2	25 km/ high northern latitudes	Solar minimum	40%	~50-60%	Next to the tanks (passenger cabin/ cockpit)
		Solar storm	49%	At most few tens of percent	

Main insights of the analysis (cf. Table 2) that may give valuable support for future design considerations and for the analysis of e.g. wetted area/shielding trade-offs are

- Due to the variation of the angular distribution of neutrons with energy (roughly isotropic up to energies around tens of MeV, mostly downwards directed for higher energies [52]), the best shielding efficiency emerges for tank layouts on top of the fuselage.
- Exceptions arise during solar storms, since here the neutron spectra do not extend up to the very highest energies such that both tank configurations achieve about equally good neutron attenuation. However, the fractional contribution of the neutron effective dose to the total one decreases with increasing altitude such that case a) would allow for the highest, impressive overall dose reduction with (at most) 58%[3].
- For tank layouts left and right of the passenger cabin the radiation exposure of pilots and crew is minimized, if the cockpit as well as the main residence area of the crew is as close as technically possible to the tanks.

Like in any other aircraft configuration inside of the aircraft a sizable, position dependent additional dose reduction would results from scattering processes of neutrons with other hydrogen containing material (e.g. baggage, cargo, humans) [53]. Liquid hydrogen is further expected to induce a decrease in the effective dose contribution stemming from cosmic protons. For the considered altitudes, the latter dominates that of neutrons during solar storms and falls second under any other solar condition [40]. A detailed analysis will follow in subsequent work [51].

In summary, clearly, the shielding ability diminishes with fuel-consumption and varies with position. Yet, in particular, the combination of liquid hydrogen as new propellant and neutron absorbing nanocomposites as novel structural material bears a significant potential for economic radiation protection in air traffic, while at the same time allowing for a sustainable growth of aviation with an extremely low impact on the environment.

5 CONCLUSION

We presented progress and challenges of future technology analysis in general and in particular of the proprietary processes at BHL. Using example cases, we demonstrated the value of the four cornerstones of BHL's "future technology analysis" methodology and elaborated on derived application potentials for aeronautics.
The first application case was concerned with introducing renewable electric energy for decarbonizing the air transport system. Fully electric aircraft and drop-in PtL fuels are potentially disruptive innovations. We presented selected aspects of key metrics, benchmarks and discussed the scaling properties and their impact on global GHG emission reduction by 2050. In contrast to fully-electric aircraft, electro-fuels are technically capable of decarbonizing air transport by 90% by 2050 (equivalent

[3] For the cosmic neutrons generated during the solar particle event, the result assumes a similar angular distribution as that presented in Ref. [53].

to the IATA goal of reducing to a 50% level in 2050 compared to 2005). The practical scaling issues limit the impact of fully-electric aircraft to around 4% GHG reduction (up to the year 2050) and the build-out of production capability for electro-fuels seems challenging as well – adding PtL fuel production capability of 3.50 Mt/a[2] equivalent to one PEARL-size PtL plant every year after 2035, after a linear ramp-up of PtL plant production capability, the total impact remains at 12.5% GHG reduction in 2050. In order to exploit functioning market mechanisms, FTA has to identify those technologies that make electro-fuel production techno-economically viable in the long-term future.

The second application case, concerned with the relevance and mitigation potentials of cosmic radiation exposure in future aviation, provided an example for future technology analysis at the intersection of technology push and pull. Main drivers found that may cause increasing radiation-induced safety concerns in aviation involve the reduction of emissions and travel time, leading to strongly growing polar route exploitation (with very high average RPK-growth rate of 26%) and to the exploration of higher flight altitudes. As key science and technology development ("push"), specifically tailored, lightweight nanocomposites were identified as possible high-performance structural materials with orders-of magnitude increased radiation shielding ability compared to e.g. aluminum. Amongst polymer composites, these nanocomposites were demonstrated to essentially reach the physical benchmark of optimized shielding performance at minimal weight penalty.

Further significant synergy potentials for radiation shielding were shown to naturally emerge from liquid hydrogen as novel propellant option for future aviation and particularly for hypersonic systems. Key insights from the analysis involve that for instance for future hydrogen powered hypersonic aircraft with tanks left and right of the passenger cabin, the radiation exposure of pilots and crew can be minimized by design. Namely, from a radiation shielding perspective, the cockpit as well as the main residence area of the crew should be as close as technically possible to the LH_2 tanks. The identification of such trade-offs may provide valuable support for future design considerations and may help to economically fly above and beyond Earth's natural radiation protection.

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