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Powering Sustainable Airports in the Year 2075

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Table of Contents

Table of Tables

Table of Figures

Abstract

This exploratory study envisions zero-carbon, sustainable hub-scale airports 50 years into the future. Our approach developed future scenarios that were framed by hypothetical levels and impacts of varied levels of future global temperature change (+1°C, +2°C, +4°C), and integrated energy generation, distribution, fuels, infrastructure, and human factors to envision three possible future states. We used backcasting methodologies by working backward from 2075 scenarios to identify the critical developments and decision points that could lead to each outcome combined with forecasting methodologies for the next ~25 years. Despite aviation's contribution to global carbon emissions, existing roadmaps to zero-carbon aviation are not presently implemented. This study also combines forecasting with backcasting methods to chart pathways to these envisioned airports, considering various Political, Economic, Social, Technological, Environmental, and Legal (PESTEL) factors. Key aspects of a future state, such as green hydrogen, multiple approaches to renewable energy, significant infrastructure changes, substantial lifecycle carbon dioxide (CO_2) reductions, and others, are highlighted as essential elements of a multi-fuel approach for sustainable aviation. Based on the core understanding of the available power alternatives, the three scenarios examine future PESTEL pathways. Specifically, the three scenarios represent distinctly different visions of airport operations in 2075, each shaped by varying assumptions about technological progress, climate impacts, and societal adaptation. While all three scenarios acknowledge the fundamental role of global temperature change, they diverge significantly on its impact and in how humanity responds to this challenge.

It should be noted that these scenarios are meant to examine differing extents of change to the present status quo with increasingly severe consequences. The ideal scenarios of abundant power depict future airports as multi-modal transportation hubs integrating advanced technologies like fusion energy, genetic engineering, artificial intelligence (AI), quantum computing, extended reality (XR) and visual computing methods applied to enhancing efficiency, security, sustainability, and passenger experience. Anticipated growth in traffic and energy demands necessitates innovative, resilient, and adaptable infrastructures. Other scenarios depict futures of climate adaptation or implemention constrained discipline in response to global changes. Key recommendations include prioritizing investments in hydrogen infrastructure, establishing a broader societal approach such as regulatory frameworks and promoting public education, examining alternate power technologies and their impact on aviation, and implementing adaptable pilot projects across an array of technologies and methods. By leveraging these insights and retaining strong communication lines from strategy to implementation, stakeholders can achieve sustainable, zero-carbon aviation, ensuring continued global connectivity and economic vitality. The overall goal of this manuscript is to inform and enable short- and long-term strategies that influence the coevolution of facilities, operations, and technology with Earth's changing environment.

Introduction

This exploratory work aims to envision zero-carbon, sustainable hub-scale airports 50 years into the future and to backcast the developments necessary to achieve these visions. By creating multiple scenarios for future zero-carbon airports, each aligned with different levels of potential global temperature change (+1°C, +2°C, and +4°C) and their possible impacts, it provides a comprehensive framework for subsequent investigations. In other words, the three scenarios each correspond to a different level of potential global temperature change not only describing the integrated energy generation, distribution, fuels, infrastructure, and human factors that led to these states, but also the response and end state that each scenario generates. These future airport visions integrate considerations of energy generation, distribution, carriers/fuels, usage, vehicle types, infrastructure, and human factors associated with the aviation and energy systems of tomorrow. Moreover, this study identifies a broad set of technology development areas that could enable or accelerate these envisioned futures, developed through a multidisciplinary approach encompassing political, economic, social, technological, environmental, and legal (PESTEL), as well as other considerations. There is an increasing realization of the need to understand and address the impact of aviation on global temperature change moving towards zero-carbon, sustainable aviation [1-3]. Although roadmaps to zero-carbon aviation, including liquid hydrogen (LH_2) technologies, were proposed five decades ago [4], they remain unimplemented. The transition to sustainable aviation is complex, and progress toward zero-carbon aviation is hindered by various PESTEL barriers. For example, related to hydrogen introduction into aviation, technical barriers encompass various fields, including the integration of future Department of Energy (DoE) regional hydrogen hubs with airport energy networks, infrastructure, and safety systems. Political, economic, and legal barriers impact rates of change, as do social obstacles such as public perception issues related to hydrogen-based fuels and nuclear energy. The combination of these PESTEL factors is a notable challenge towards enabling a future hydrogen economy. Social, economic, and environmental changes can be as crucial as technology advancements in adoption of this new paradigm.

Transitioning to sustainable aviation will necessitate expansive investment in policies, technologies, economies, and communities over time. Multiple types of technology, alongside significant changes in infrastructure and society, will be essential to achieve sustainable aviation in the future. There is currently no immediate pathway to convert to sustainable aviation; such a transition will need to occur progressively, involving both aviation and societal changes. As noted, various external factors can significantly impact the development of sustainable airport infrastructure. While aviation is a notable contributor to global carbon emissions, producing over 3%, it is not the sole driver of global temperature change or a changing energy landscape.

Airports currently serve as critical travel, economic, and cultural hubs, connecting diverse populations and facilitating global exchange. These transportation centers contribute significantly to local economies. In the United States alone, commercial airports generated over $1.4 trillion in economic output in 2017, supporting more than 11.5 million jobs and representing over 7% of the nation's gross domestic product (GDP) [5,6]. North American airports handled more than 1.8 billion passengers in 2017, while global passenger traffic exceeded 8.2 billion [7,8]. While COVID notably impacted air travel, growth has continued with commercial airports generating over $1.8 trillion in economic output in 2024 and supporting more than 12.8 million jobs [9], with the Airports Council International forecasting a doubling of global passenger traffic by 2034 [10].

Future Forecasting and Backcasting Process

The approach in this work is to combine multiple methods of characterizing the past, present, and future. This research first involves understanding past and present trends to forecast likely futures, considering a wide spectrum of influencing factors. Further, to avoid the limitations of forecasting based on past thinking, backcasting is employed to envision the future through three distinct scenarios described in more detail in Section V related to different levels of global temperature change, each with roadmaps to potential future states using benchmarks, drivers, and other causal indicators. These scenarios incorporate PESTEL factors. Core features of each scenario are described through detailed models and rationale, identifying technology enablers, benchmarks, drivers, and end-state features essential for achieving the envisioned scenarios. Additionally, pivot points in the roadmaps are identified as defining moments that facilitate the envisioned future. We also interviewed Subject Matter Experts (SMEs) to assist in our understanding of the benchmarks and drivers associated with various stakeholders. Finally, we summarize key findings and high-level strategic suggestions for further research.

Over the past 50 years, the core foundations of jet fueled aviation has remained relatively unchanged but there has been advancement in more powerful, quieter and energy efficient jet engines, composite materials, and advanced air traffic management. However, these foundations are now on the cusp of significant transformations with possible increase in vehicle-types in mixed-use airspace, or the core fuels used for aviation. While there is some ability to forecast the next 25 years, such predictions are fraught with uncertainties and numerous variables. Multiple initiatives aim not only to roadmap for 25 years into the future but also to actively develop technologies for that time frame. However, focusing solely on a 25-year horizon may be insufficient to fully grasp the impact of these impending changes. The year 2050 is frequently cited as a target for achieving net zero emissions, yet substantial consequences could arise if this objective is not met, proves inadequate, or is impacted by other large-scale events. Additionally, the pace of global temperature change and its effects may be accelerating faster than anticipated, with numerous significant impacts occurring after two decades [11]. This study seeks to address what can be done to prepare for such potential futures and what measures should be taken to mitigate threats. Overall, it aims to complement current efforts and extend the understanding of longer-term impacts.

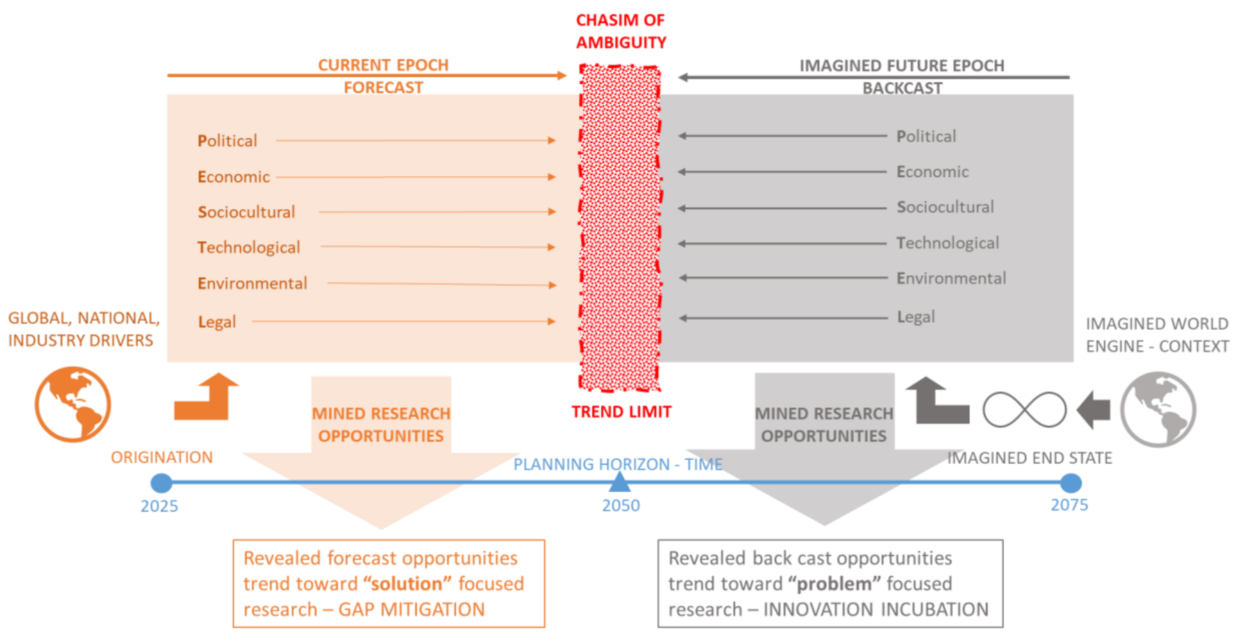

Figure 1: Forecasting and Backcasting Process

A study timeframe of 50 years from now was chosen to allow for a broader vision of the future and to target the conditions necessary to make that vision a reality. In this wider context, we can begin to identify the foundational steps that must be taken to either avoid or adapt to a world that could be increasingly impacted by global temperature change and other factors. We first explore forecasting for the next 25 years, then backcast from 50 years from now. In other words, our planning methods started with defining a desirable future and then working backward to identify the steps necessary to achieve that future (Figure 1). Backcasting can help to connect shorter term forecasting with a well-conceived future state scenario. While there are an indeterminate number of future states, a foundation is essential to decide which states warrant further consideration. Our approach is fundamentally related to energy availability, environmental and economic sustainability, and intrinsically tied to global temperature change and its potentially catastrophic impacts. Thus, envisioned future states were selected based on 3 possible climate futures using three distinct increases in global temperature warming and their impacts. Although a long-term roadmap for the next 50 years of aviation cannot be fully provided, this work may serve as an initial step in that direction.

Future Aviation Energy Needs and Production

Energy needs are expected to grow dramatically in the next 50 years [12,13]. The main drivers of forecasted energy demand are population growth, economic development urbanization, and ongoing electrification requirements of emerging technologies and infrastructural requirements [14].

Figure 2 shows the projected population growth given differing assumptions with a median projection of 11 billion in 2100 [1]. Current methods of energy generation are incapable of meeting forecasted energy demand, especially if that demand is to be met sustainably. In 2020, global energy production was 153 PetaWatt hours (PWh) [15]. Estimates for 2060 have 261 PWh extrapolation from that number suggests a power need of at least 264 PWh by 2075. Extrapolating from the projected 261 PWh energy demand in 2060 (using a conservative annual growth rate of approximately 0.2%) calculations indicate a minimum energy requirement of 264 PWh by 2075, highlighting the necessity for alternative energy production methods to sustain human advancement.

In this study, the application of forecasting methods to current airport energy technologies, combined with backcasting from our desired sustainable future state, reveals several critical pathways for powering tomorrow's aviation infrastructure. These include multiple fuel types: Hydrogen, Sustainable Aviation Fuels (SAFs), and Multi-Fuel Economy, followed by zero-carbon methods to produce fuels and energy: Nuclear Fission & Fusion, and Solar. These fuels and energy production methods are discussed in this section.

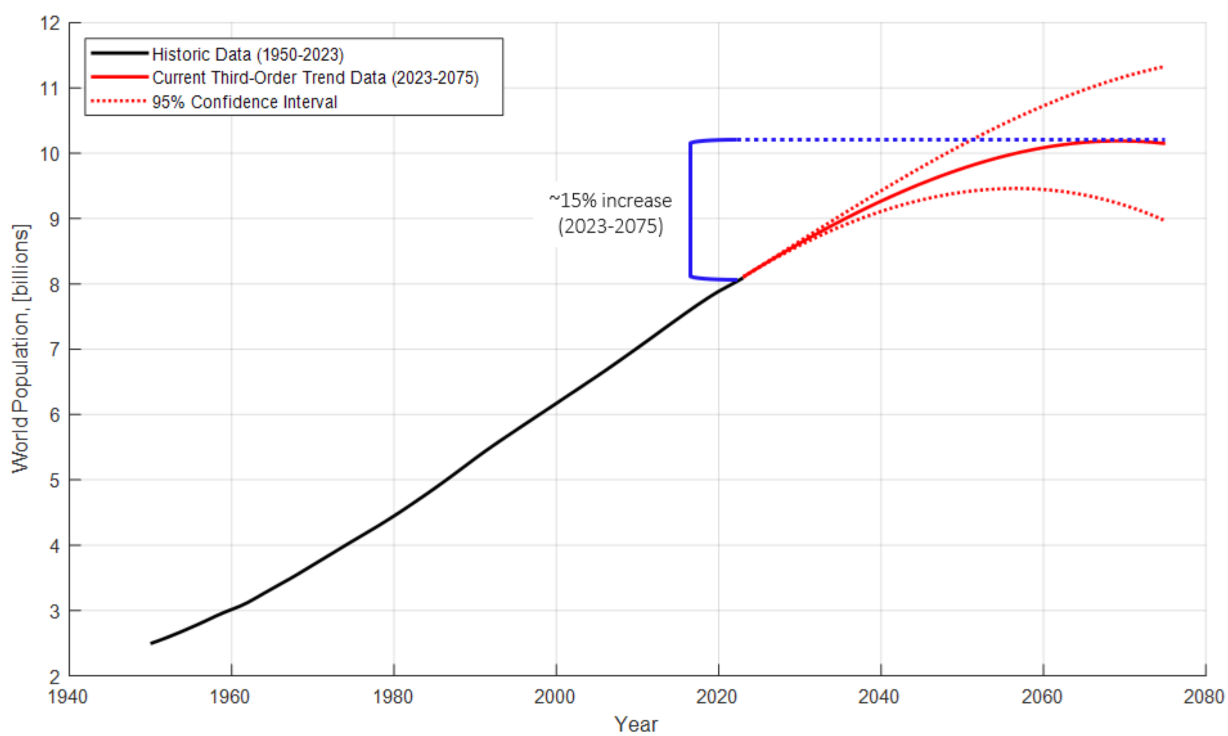

Figure 2: Estimates World Total Population from 1950 to 2100 (1)

Sustainable Aviation Fuels

Sustainable Aviation Fuels (SAFs) offer a potential and temporary pathway for emissions reduction in the aviation industry, potentially decreasing life-cycle CO_2 emissions compared to traditional jet fuel, depending on the production, use, and storage methods. The production of SAFs includes the use of both feedstock and traditional jet fuel. Each gallon of “neat” SAF, from non-petroleum based renewable feedstock, that replaces conventional jet fuel can reduce full-fuel-cycle greenhouse gas emissions by approximately 60-75% [16,17]. SAFs are technologically compatible as drop-in fuels, requiring no significant modifications to jet engines or fuel storage and dispensing systems. Although current regulations mandate that SAFs must be blended with at least 50% conventional jet fuel, the use of 100% SAF may be possible soon. This compatibility may enable a relatively seamless transition to more sustainable fuel options without necessitating costly fleet overhauls.

Despite these advantages, the market for SAFs is still in its nascent stages. Global SAF production tripled from 2021 to 2022, but it still accounts for less than 0.1% of what is needed to meet net-zero targets by 2050 [18, 19]. Major companies and airlines are investing in SAF production and committing to usage goals. Government initiatives, such as the U.S. "SAF Grand Challenge," aim to scale SAF production to 3 billion gallons per year by 2030 and 35 billion by 2050 [20]. However, challenges remain, including the current low production levels and costs that are 3 to 5 times higher than conventional jet fuel. Additionally, the limited availability of biogenic feedstocks poses a significant hurdle for scaling up production. To address these issues, the industry is exploring advanced production pathways such as e-SAF, which combines green hydrogen with captured CO_2, and increasing investments in research and development for third-generation feedstocks and e-fuel production. Policy support and financial incentives are also deemed crucial to de-risk investments and create a robust market for SAFs.

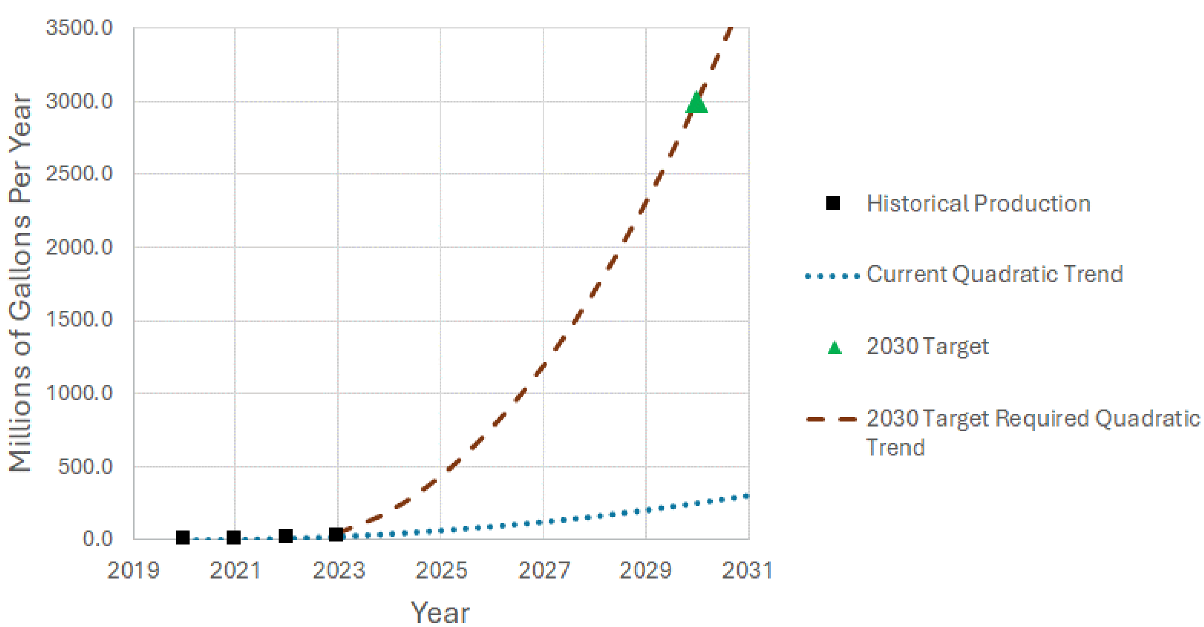

Figure 3: History and Projections of SAFs production.

However, changes to enable targeted SAFs productions will need to be significant to meet targeted goals. Figure 3 [21] shows the recent historical trend of SAFs production, an extrapolation of trend to the year 2031 (in blue), as well as the FAA target of 3 billion a year by

2030. Historical data of SAF production when extrapolated forward miss both the 3-billion-gallon (2030) and 35 billion gallon (2050) targets. In this study, and as shown in Figure 3, there exists a substantial difference between the 2030 SAF production target and the current trajectory of SAF production capabilities. Although the present trend is a quadratic increase in SAF production, significant rate increase is needed to meet the proposed 2030 target (red line), and it is not clear that this target is viable without significantly increase investment and infrastructure changes.

Potential Zero-Carbon Aviation Energy Carriers

While aviation decarbonization requires multiple solutions, selecting appropriate energy carriers demands careful consideration of energy density, safety, infrastructure requirements, and environmental impact. Hydrogen has emerged as a promising option due to its high gravimetric energy density and zero-carbon emissions at point of use. However, alternatives like ammonia (NH_3) offer compelling advantages, including higher volumetric energy density (12.7 MJ/L vs. hydrogen's 8.5 MJ/L), storage at milder temperatures (-33°C vs. hydrogen's -253°C), reduced flammability, and existing global infrastructure with approximately 180 million metric tons produced annually [22]. Despite these benefits, ammonia still presents significant challenges including toxicity, production energy requirements, and potential nitrous oxide emissions that are approximately 300 times more potent greenhouse gases than CO_2. Other potential carriers such as synthetic e-fuels and advanced biofuels offer drop-in compatibility with existing infrastructure but also face scalability and sustainability challenges. Battery electric systems, while promising for short-range flights, remain limited by insufficient energy density for long-haul aviation. This multi-criteria analysis reinforces hydrogen's position as a pivotal bridge technology while acknowledging the ongoing need to evaluate alternatives within specific operational contexts.

Hydrogen Production and Usage

While multiple energy solutions show promise, hydrogen appears to be a pivotal technology that bridges current capabilities with future requirements, though its implementation presents significant infrastructure and efficiency challenges. Producing green hydrogen at a single large hub airport will require electricity on a scale comparable to that of a large, several-gigawatt nuclear fission power plant [23-27]. Current technology readiness indicates that 79% of the electricity used in Liquid Hydrogen (LH_2) production is lost due to inefficiencies in the electrolyzer, liquefaction process, boil-off, and propulsive inefficiencies, with only 21% translating into useful work or aerodynamic drag reduction [28-31]. There are three primary scenarios for hydrogen generation and liquefaction as seen in

Figure 4 [32]. These include (1) off-site hydrogen generation and liquefaction supplied to the airport by road tankers, (2) off-site hydrogen generation with on-site liquefaction supplied by gas pipeline to the airport, and (3) on-site hydrogen generation and liquefaction. The approach adopted depends on the individual airport and may evolve as hydrogen becomes more dominant as a fuel.

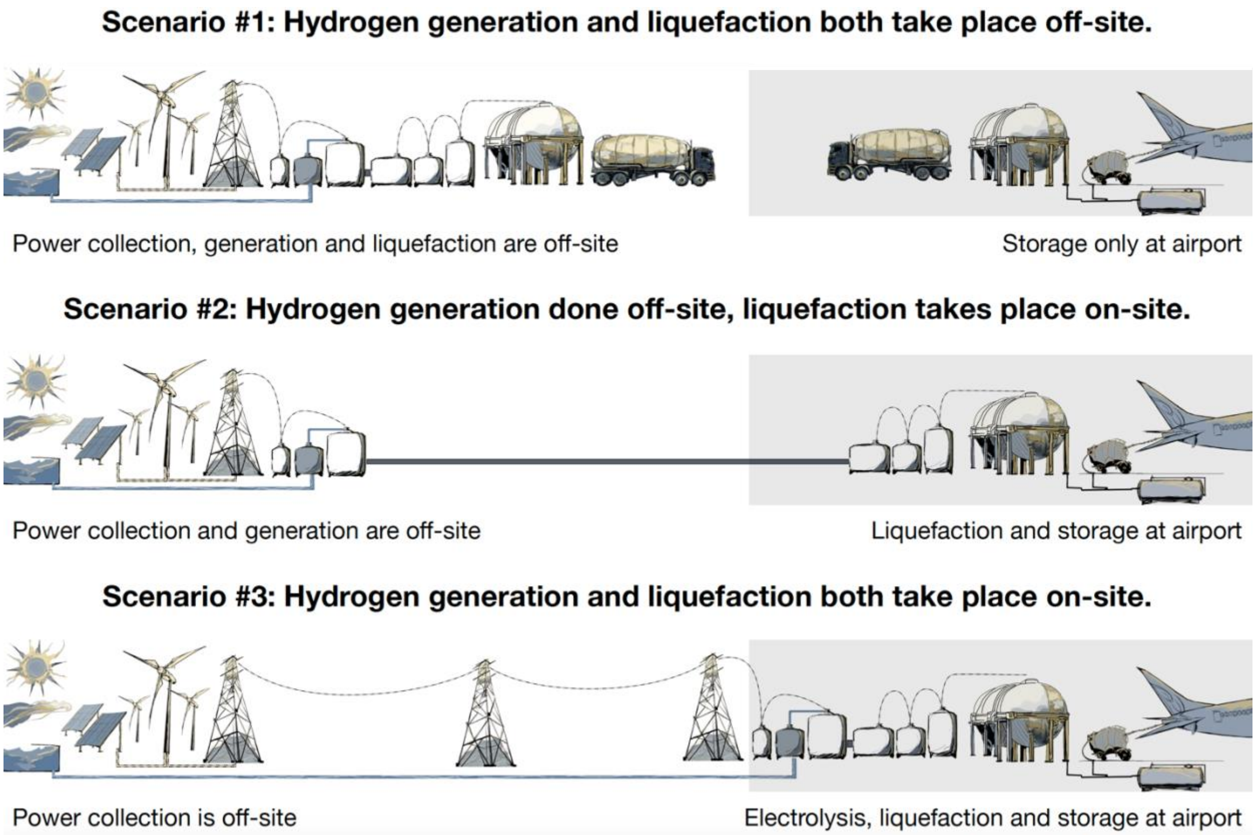

Figure 4: Hydrogen Generation and Delivery Infrastructure Options (2)

In the evolution of hydrogen usage in aviation, European projections indicate the deployment of various types of hydrogen-powered aircraft [24-26]. Small commuter aircraft will likely adopt hybrid-electric systems with conventional kerosene-powered gas turbines for fewer than 19 seats. Regional aircraft, with 40 to 100 seats, are expected to incorporate liquid hydrogen fuel cells, while short and medium-range aircraft with 160 to 250 seats may use turbofan propulsion systems that directly combust liquid hydrogen. Long haul or "widebody" aircraft are expected to be the last segment of the aviation industry to adopt hydrogen fuel due to the strict fuel requirements needed to achieve intercontinental ranges [27]. According to McKinsey's 2020 study for CleanSky 2 and Fuel Cells and Hydrogen 2 JU (FCH 2JU), the European Union and associated regions could see 375 hydrogen fuel cell aircraft and 1,093 hydrogen turbofan aircraft by 2040 [28-29]. Furthermore, battery-electric and hybrid-electric aircraft are anticipated to enter service by 2030, with projections of 134 such aircraft operating globally by 2035, of which 29 are expected in the European Union/ European Economic Area/Switzerland/United Kingdom (EU/EEA/CH/UK) regions. A whitepaper by ZeroAvia [30] predicts by 2040, the number of hydrogen fuel cell and turbofan aircraft is forecasted to reach 1,885 and 5,795, respectively, out of 9,914 new aircraft globally. This work estimates that around 14 million flights will be hydrogen-powered by 2040, out of 45 million total flights globally, increasing to 32 million hydrogen-powered flights out of 50 million by 2050. The global demand for hydrogen would then rise from 2.6 million tons in 2035 to 36.8 million tons by 2050. Such a demand will necessitate a vast investment in infrastructure and economic changes.

The aviation industry's strategic trajectory entails the integration of hydrogen from on-airport equipment by 2025, proceeding with Boeing's short-range hydrogen flights between 2030-2035, and mid-range flights entering service in line with World Economic Forum timelines [31]. Full regulatory compliance, anticipated over the next 10-15 years, will be crucial in achieving industry milestones and transitioning towards zero-emission aircraft by manufacturers such as Airbus and Embraer by 2035. This regulatory acceptance must be coupled with economic viability.

Hydrogen Adoption Economics: A Game-Theoretic Analysis

The transition to hydrogen-fueled aircraft presents a complex interplay of economic factors, technological challenges, and strategic decision-making. As part of this project, we examined this potential adoption through a game-theoretic lens, focusing on the economic viability and strategic considerations by airlines and airports driving industry-wide transformation towards hydrogen aviation.

Airlines must balance the costs of hydrogen-fueled passenger miles against infrastructure availability. Our model assumes airlines optimize their fleet composition between conventional (Jet A/Kerosene/SAF) and hydrogen-based aircraft to minimize operational costs while meeting passenger demand. This optimization depends heavily on the network of airports capable of servicing hydrogen aircraft, creating a critical dependency between airline strategies and airport infrastructure investments.

Airports also face substantial upfront costs in adopting hydrogen infrastructure. Their investment decisions derive from net present value analysis, weighing future revenue streams against installation expenses. The value proposition improves as peer adoption increases, creating network effects that can accelerate or hinder industry-wide adoption. This interdependence forms the basis of a complex, multi-player game with multiple potential equilibrium points.

Figure 5 shows the results of a hydrogen adoption model based on game theory. The actors in this game theory are the airports and the airlines with different and potentially conflicting interests. Airports need to invest in LH_2 infrastructure to provide the required aeronautical services to hydrogen powered aircraft. Airlines need to invest in hydrogen powered aircraft and demand aeronautical services. Airports will have no incentive to adopt LH_2 if both airlines and other airports don't also adopt LH_2. Airlines will similarly have little incentive to adopt LH_2 aircraft if airports cannot provide fuel and other aeronautical services. Both airports and airlines must make rational decisions based on what is in their own private best interest. The equilibrium in this hydrogen adoption model is characterized as a subgame perfect Nash Equilibrium (NE), derived through backward induction in a two-stage game.

Mathematically, it is represented as a fixed point of the equation (1) where S represents the proportion of airport adopters, G(·) is the cumulative distribution function of airport capacities, and α(S) is the airline industry's best response function. This equilibrium requires numerical solution due to the nonlinear nature of equation (2).

$$S = 1 - G\left(\frac{X(\delta-\gamma)}{F_H a(S) S}\right) \quad (1)$$

$$a(S) = \left[p_H^{\left(\rho/(\rho-1)\right)} S^{\left(\rho/(\rho-1)\right)} + S\right]^{-1/\rho} \quad (2)$$

The model parameters include consideration of various aspects the implementation of transition from jet fuel to hydrogen. These include: X: minimum fixed capital expenditure to install LH_2 at an airport; δ: discount rate; γ: growth rate of airport fees; F_H: hydrogen airport fees; p_H: effective price of LH_2 at point of sale to airlines; ρ: elasticity of substitution of hydrogen and JetA/Kerosene passenger miles for one another. Passenger demand for flight is not explicitly modeled and it is assumed that passengers are indifferent to the fuel or technology used to fly them to their destination if the overall passenger experience is equivalent. It also assumes that hydrogen flights will not be priced outside of consumer interest. The resulting interaction between airlines and airports, modeled as a two-stage game using the above equations and approach, reveals in Figure 5 three distinct equilibria in market evolution: zero adoption and two intermediate levels (approximately 50% and 75% adoption). The model suggests that significant initial adoption, likely requiring government intervention, is necessary to shift the industry toward positive outcomes. Figure 5 suggests this government intervention results a tipping point in hydrogen usage in the market near 2050 with widespread adoption of hydrogen aircraft by 2055. The most critical factors affecting equilibrium are: (1) initial adoption rate, as the model exhibits tipping point behavior requiring critical mass; (2) relative price of hydrogen, directly impacting airline demand and airport adoption incentives; and (3) distribution of airport capacities, where small changes can significantly alter equilibrium outcomes due to nonlinear interactions.

The adoption of hydrogen-fueled aviation thus requires a complex interplay between airline cost considerations and airport infrastructure investments, leading to potential equilibrium states that may not result in complete industry-wide adoption, despite the technology's promise. These findings highlight the complex dynamics of technological transition in aviation and underscore the importance of coordinated efforts and policy interventions to overcome initial adoption barriers.

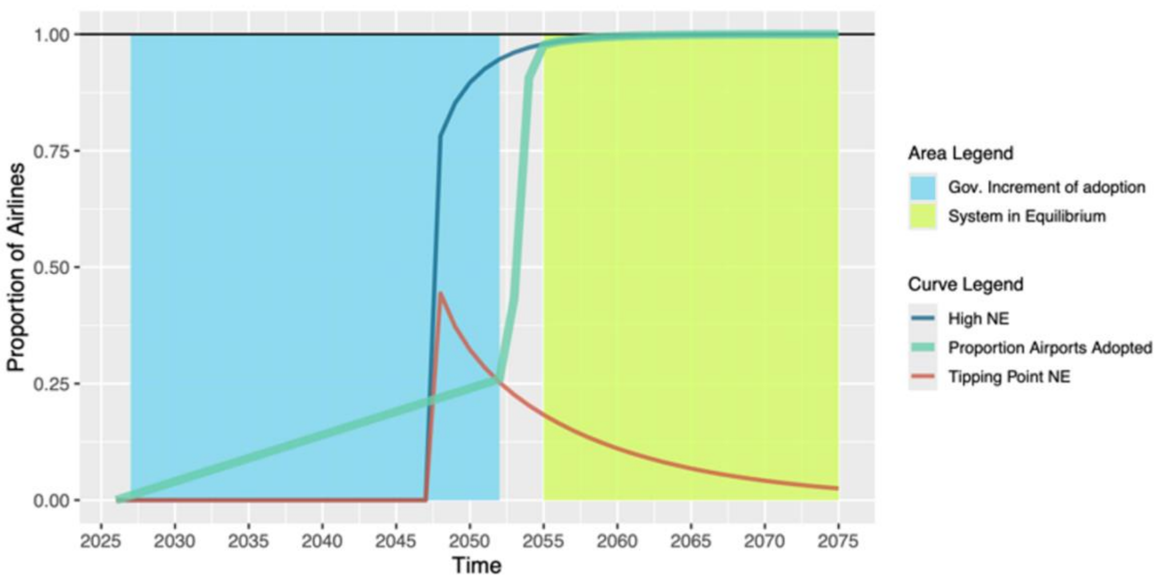

Figure 5: Hydrogen Adoption Model Generated Showing the Market Evolution to Nash Equilibrium (NE) of Hydrogen Adoptions.

Multi-Fuel Economy

The need to reduce aviation's reliance on fossil fuels, currently at 14.47 billion gallons of jet fuel annually (2023), necessitates comprehensive strategic planning to support the adoption of SAFs, hydrogen, and other alternative fuels. Given present trends, we are entering an age where a single energy carrier/fuel solution will no longer dominate. Outside the aviation industry, technologies such as solar, wind, battery, hydro and others are being developed to complement and potentially replace traditional energy sources. A similar shift is anticipated in aviation, where a combination of innovative energy solutions will be required to power future aircraft. These solutions may include Jet-A, SAFs, Liquid Hydrogen (LH_2), Gaseous Hydrogen (GH_2), Ammonia (NH_3), Fuel Cells, battery-electric systems, and hybrid-electric propulsion. Each has its advantages and disadvantages. For example, ammonia is an option to hydrogen due to its increased power density, but there are challenges, for example, in its handling and amount of energy needed for its production.

Figure 6 [32] suggests that by 2050, up to 38% (green) of the global fleet will be collectively zero carbon utilizing different forms of alternative power sources. This diversification in energy sources aims to address the evolving needs of the aviation industry while promoting sustainability and efficiency. Overall, the introduction of battery-based or hydrogen fueled flights will take time for complete implementation. Thus, in the nearer term, the use of SAFs as well as other power sources are expected in an evolving multi-fuel economy.

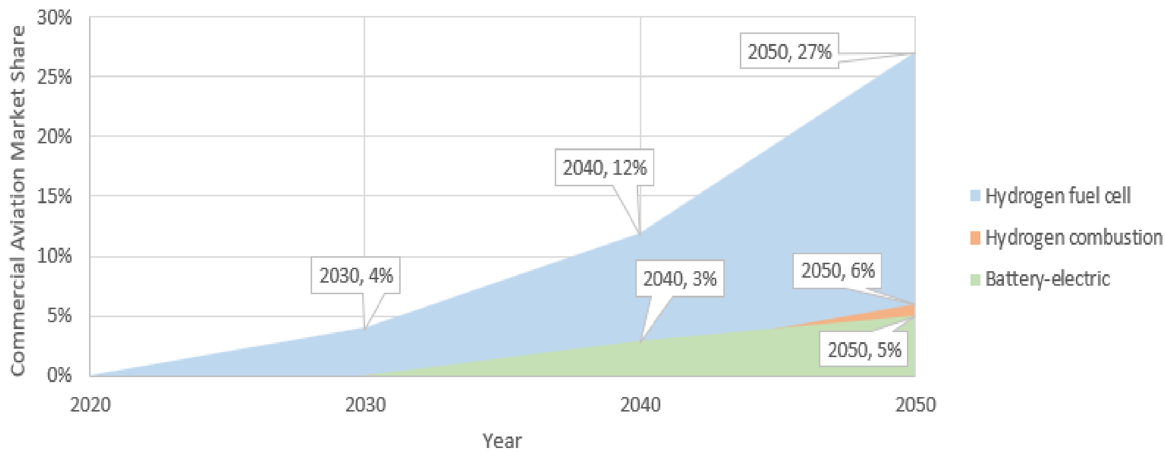

Figure 6: Zero-carbon propulsion adoption timeline (% global fleet/optimistic scenario). Derived from Ref. (3).

Nuclear Fission & Fusion

Current methods of energy generation will struggle to meet forecasted energy demand, necessitating alternative means of production for human civilization to grow and advance. A primary prospect to close the energy demand gap currently lies in fusion-based energy production. For context, Palo Verde, the largest nuclear fission power plant in the U.S., has an electricity generating capacity of 3,937 megawatts (MW) and in 2022 generated approximately 30 TWh of energy [33,34]. Nuclear fusion, however, promises an increase in electrical production by up to four times over conventional nuclear fission power plants [35, 36]. Nuclear fusion releases nearly four million times more energy than fossil fuels [36]. Further, assuming a Palo Verde-sized fusion power plant could generate 90 TWh (three times 30 TWh), only 1,170 fusion power plants could generate 108 PWh, significantly addressing the anticipated energy shortfall [37, 38]. Thus, the realization of fusion as a widely distributed power source is a key enabling technology for generating large amounts of sustainable power. However, large scale fusion power sources do not presently exist.

Nonetheless, progress toward net energy gain and commercial viability in fusion energy is promising, although no single project currently aims to produce energy in the next few years, despite an investment of $6 billion to date [39]. The first fusion power plants are expected in the early 2030s while full infrastructural implementation may not arrive until the 2050s or 2060s [40]. Notable progress currently being made in this domain include Commonwealth Fusion's SPARC device , TAE Technologies' "Norman" reactor, General Fusion's magnetized target fusion, Tokamak Energy's compact spherical tokamak, Helion Energy's pulsed magnetic fusion engine, and the ITER international collaboration aiming for its first plasma within the coming decade [41]. For comparison, the JET fusion experiment produced 59 megajoules over a five-second period, averaging around 11 megawatts of fusion power [42]. Scaling this up to a full-scale power plant operating continuously could theoretically yield much higher outputs.

However, it's crucial to note that significant technological advancements are still required before fusion can be commercially viable. Challenges include developing materials that can withstand extreme conditions, achieving sustained fusion reactions, and efficiently converting fusion energy into electricity [38, 43]. Additionally, while fusion has the potential for high energy density, the power density of fusion reactions in gas is lower than fission reactions in solid fuel, so which means fusion reactors would need to be larger and potentially more costly than fission reactors for the same power output [43]. While the stated energy production from fusion power plants is theoretically possible given fusion's potential, it remains a future goal that requires scientific and engineering breakthroughs to achieve.

In the context of fission power, there are approximately 413 to 436 operational nuclear fission reactors worldwide as of 2023, located in 30 to 32 countries, with a combined power capacity of about 390 gigawatts electric (GWe) contributing roughly 10% of global electricity production [44-46]. Additionally, around 60 reactors are currently under construction. In contrast, coal-fired power plants have a global capacity of approximately 2,130 gigawatts as of 2023, with China, India, and the United States hosting 1,100, 285, and approximately 240 plants, respectively. Including retired, operating, and planned units, there are around 3,000 gigawatts of coal power across 99 countries [47, 48]. Thus, nuclear fission presently produces a small percentage of energy compared to that of conventional coal power plants. The expansion of nuclear fission, including the use of small fission reactors, could notably change the energy production landscape [43, 49-55] although a range of societal issues, such as political and/or environmental concerns could limit such expansion. These political and environmental concerns include the possible impact of nuclear accidents on the public and safe disposal of nuclear waste.

NPIAS Sustainable Solar Production Study

A fundamental challenge with respect to sustainable aviation is a definition of the power source and how that source would interface with the aviation system. As a test case, this project investigated one potential source of power generation by looking at solar power generated on the landmass associated with the National Plan of Integrated Airport Systems (NPIAS). This internal project study compiled data presented in Appendix A drawing from public sources related to the available NPIAS landmass. The project then analyzed the data to estimate how much power could be by solar power from this landmass. Figure 7: NPIAS Virtual Power Utility Overview (See Appendix A) provides a visual summary of the results.

NPIAS encompasses 682,972 acres of available land [56], presenting a substantial opportunity for solar energy generation. Total land for each NPIAS airport is reported via FAA Form 5010. The total land area available for each NPIAS airport is derived and requires confirmation via site survey. This acreage, when utilized, could significantly contribute to on-site energy needs and support broader energy transitions within aviation. The expansive acreage holds the potential to generate approximately 380 terawatt-hour (TWh) of solar energy annually. This estimation incorporates a ±15% availability variance, accounting for site-specific conditions and installation efficiencies. The potential energy production assumes a conservative capacity of 200 kW per acre [57] and providing a robust foundation for renewable energy deployment across airport facilities. The cumulative base load requirements for non-hub General Aviation airports are estimated at 11 TWh, whereas the other small-, medium-, and large-hub airports demand are estimated at approximately 1.7 TWh annually. Consequently, a substantial surplus of 367 TWh remains available, underscoring the capacity of airport landscapes to not only satisfy internal energy demands but also contribute excess power to the grid, reinforcing a sustainable aviation infrastructure. Replacing jet fuel with liquid hydrogen (LH_2) would require approximately 1,004 TWh, assuming a 53% efficiency in electrolysis and liquefaction processes. The power generated by the NPIAS system in this scenario would then provide near 37% of this energy.

This study provides a theoretical framework showing a pathway to a sustainable energy future based only on solar power and using hydrogen. The same approach is also relevant for other parts of the country where solar power may be less prevalent, and rather notable amounts of power might be generated by, e.g., the use of wind or local hydro sources. A fundamental point is that by reconceiving the nature of the airport and associated landmass, new approaches towards sustainability may be viable.

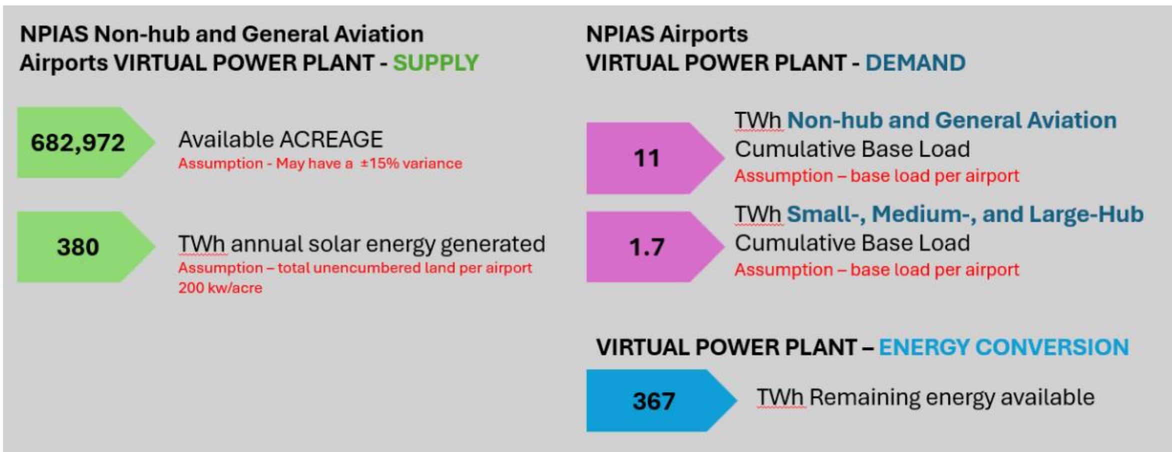

Figure 7: NPIAS Virtual Power Utility Overview (See Appendix A)

Water Challenges

Alternate power sources can have their own environmental and societal impact; full accounting of these impacts is needed. For example, a challenge in the transition to an alternate energy future includes the impact on other natural resources, such as water. For hydrogen, electrolysis water usage is significant, especially for drought-prone regions, but it is unlikely to overwhelm the U.S. water supply. However, the purity of water required for electrolysis needs to be approximately 99.9%, and global water availability varies significantly [58-60]. Arid desert regions are expected to become more vulnerable to drought conditions as global temperature change progresses. Approximately 122 billion gallons of water would be required annually for electrolysis to meet the 2023 commercial aviation demand [61-63], constituting only about 0.12% of the current U.S. annual water usage [64, 65] yet posing part of an overall water challenge. As seen in Figure 8: Water Consumption of Various Hydrogen Production Pathways (4)Figure 8 [6], some approaches for hydrogen generation use more water than others. There is potential to reduce water usage in the industrial processes with hydrogen production, and electrolysis technology is expected to become more efficient over time.

The production of SAF presents opportunities and challenges, particularly concerning water usage. This section outlines the water requirements across various production pathways and examines broader implications within the context of global temperature change and resource management. SAF production encompasses several methods, each with distinct water demands. Notably, the Power-to-Liquid eSAF (Electro-Sustainable Aviation Fuel) process, adopted by companies like Twelve [67], entails significant water input to produce fuel from water and CO_2. Another advanced method, Solar Thermochemical Jet Fuel production, demonstrates a substantial water footprint, requiring approximately 49.8 liters per liter of jet fuel produced, indicating both direct (7.4 liters) and indirect (42.4 liters) water demands [68]. The Federal Aviation Administration (FAA) has been active in promoting SAF development, partnering with industry stakeholders through the Commercial Aviation Alternative Fuel Initiative (CAAFI) and spearheading the "SAF Grand Challenge" to reach ambitious production goals. Despite these initiatives, the water requirements for SAF production can surpass those of conventional jet fuel, particularly when employing crop-based feedstocks that necessitate irrigation for cultivation. The unblended form of SAF (neat) achieves a notable reduction in life-cycle greenhouse gas emissions (as noted above), however, current regulations mandate a blend with conventional jet fuel, sustaining challenges associated with cost and availability.

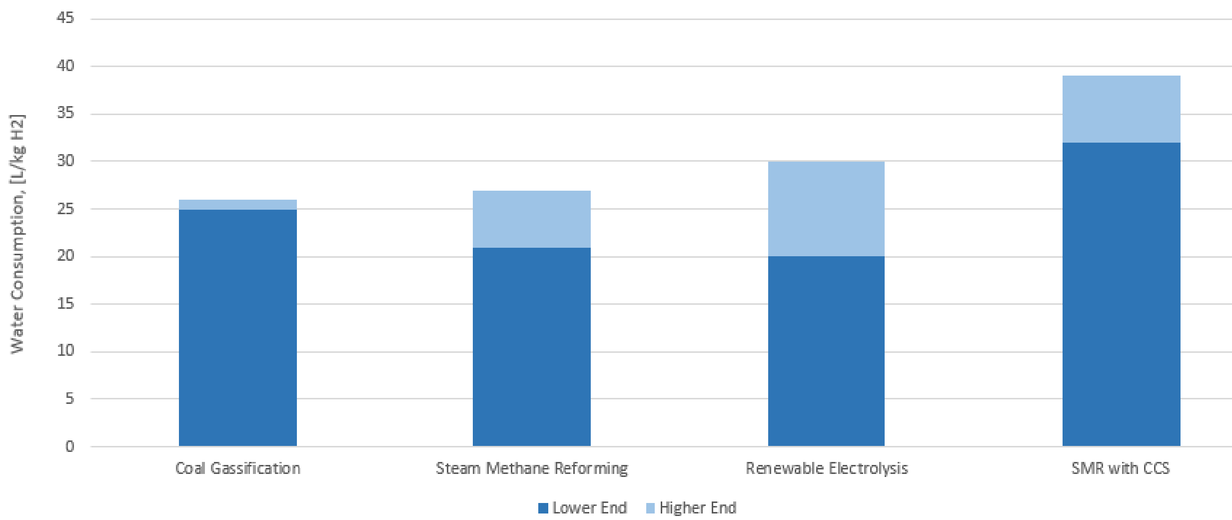

Figure 8: Water Consumption of Various Hydrogen Production Pathways (4)

The implications of expanding SAF production, alongside the deployment of hydrogen-based fuels, pose potential resource conflicts in water-stressed regions, especially given projections of severe water shortages in areas like the American West. According to historical data, regions such as the central and southern Great Plains, the Southwest, and parts of California are already experiencing acute water crises. With the anticipated growth of SAF production, it is imperative to incorporate sustainable resource management practices. This includes utilizing non-traditional water sources such as seawater, industrial wastewater, or municipal wastewater, potentially increasing production costs minimally but alleviating pressures on freshwater systems. Further, strategic siting of SAF production facilities away from high-water-stress regions can mitigate local resource conflicts. The estimated water usage for SAF and green hydrogen production underscores the need for technological advancements and integrated water management strategies to ensure environmental sustainability. Implementing recycling technologies, optimizing feedstock selection, and adhering to robust policy frameworks will be critical to balancing the environmental footprint of SAF production with the increasing demand for SAF. This integrative approach is vital for fostering a transition to a low-carbon, resource-efficient aviation industry.

Solar and Other Power Sources

Solar power has the potential to be a major contributor to the global energy mix, but realizing this potential requires advancements in technology, infrastructure development, and supportive policy changes. To meet the energy demand equivalent to 10 petawatt-hours (projected annual energy requirement for 2050), an area of approximately 19,500 km², or roughly 25% of the Mojave Desert, would be required for solar installations [69]. Technological advancements are crucial for maximizing solar power generation. Increasing the efficiency of solar cells through innovations in materials, cell design, and light-trapping techniques will help capture more energy from sunlight. Concentrated Solar Power (CSP) systems can achieve higher temperatures and efficiencies with improvements in mirrors, heat storage, and turbines. Emerging technologies like perovskite solar cells, biophotovoltaics, bifacial solar panels, quantum-dot photovoltaics, low-emissivity glass (LOE) collection, and other emerging technologies which offer improved efficiency and the potential for low-cost manufacturing, require further research to address stability and scalability concerns. Solar panel efficiencies show consistent improvement over the last three decades with current single-junction technologies approaching 30% efficiencies and multijunction technologies approaching 50% [70].

Infrastructure development is equally important to support large-scale solar power integration. Expanding and modernizing power grids, alongside the implementation of energy storage solutions like batteries, pumped hydro, and thermal storage, can help balance supply and demand. Smart grid technologies can optimize solar power distribution and integration, while microgrids can enhance resilience, reduce cost and pricing, and enable local energy generation and consumption. Policy changes are also necessary to drive solar adoption. Financial incentives such as government subsidies, tax credits, and feed-in tariffs can encourage investment in solar power and methods including wind, maritime, geothermal, and many others. Regulatory reforms that streamline permitting processes and establish clear guidelines can facilitate solar project development. International cooperation can promote knowledge sharing, technology transfer, and the establishment of standardized policies. Moreover, increased investment in research and development is essential to drive innovation and reduce costs. We foresee great potential in hybrid and multi-modal collection from coordinated sources to improve resilience, independence, and redundant power supply methods.

As we see in utility-scale energy generation outside aviation, solar, wind, battery, and hydro are all being developed to fill the gaps of traditional power generation. We anticipate a similar shift in aviation. Some combination of the following will be needed to power aircraft in the future: Jet-A, SAFs, LH_2, GH_2, NH_3, Fuel Cells, battery-electric, and hybrid-electric. As one extends into beyond 2050, this study suggests that beyond 2050 it is expected that solar energy dominates, with maritime energy showing significant growth, surpassing wind in long-term projections. Wind energy contributes steadily, with the most conservative growth projection.

An Overview of Significant Future Trends and Technologies

Overall, the nature of air travel in 2075 is expected to be significantly different from today, shaped by technological advancements, changing social norms, and evolving economic factors (as well as the predominant climate and environmental factors as highlighted in the scenarios below). The global aviation industry is projected to experience continued growth, with passenger numbers expected to increase by 3.8% annually over the next two decades, resulting in over 4 billion additional passenger journeys by 2043 compared to 2023 [71]. The Asia Pacific region is anticipated to lead this growth, contributing to more than half of the global net gain in passenger numbers and accounting for nearly half of global passenger traffic by 2043 [71]. Urbanization trends will likely impact air travel patterns, with the potential for a more distributed network of smaller airports serving decentralized communities. The expansion of aviation has already significantly influenced urban development, reshaping spatial dynamics and land use patterns around airports [72]. This trend may continue, with airports serving as focal points for suburban growth and mixed-use development [72]. Technological advancements could also lead to more efficient and environmentally friendly aircraft. Airbus, for instance, predicts continued annual growth of 4.4% in revenue passenger kilometers (RPK) for the next two decades [73]. However, the nature of air travel may shift towards more leisure-oriented trips as remote work reduces the need for frequent business travel. This could result in a preference for longer, more cost-effective journeys over short-haul flights. Additionally, the integration of advanced technologies like biometrics and AI-driven systems could streamline the airport experience and improve efficiency [74]. While these projections offer a glimpse into the potential future of air travel, it's important to note that significant uncertainties remain, including geopolitical tensions, economic fluctuations, and the pace of technological advancements [71].

Other power generation considerations include energy systems combining solar, wind and power via maritime applications are being developed, but they do not currently include fusion power. Aquarius MRE (Marine Renewable Energy) is a patented solution that combines sail power using rigid sails with solar power for ships1 [75-77]. This system aims to reduce fuel consumption and harmful emissions in commercial ocean-going vessels [75-77]. While solar and wind power are increasingly used in maritime shipping, nuclear (fission or fusion) power is not yet commercially viable or integrated into these systems. As generally discussed above, current fusion experiments have only recently achieved net energy gain, with the National Ignition Facility reporting a gain factor of 1.5 in 2022, far below the stated factor of 50. The ability to recover tritium from a range of sources can enable future nuclear fusion capabilities.

Regarding biodiversity conservation, urban green spaces do play a crucial role. They provide habitats for various species, promote biodiversity, and create wildlife corridors in urban environments [78]. These spaces, including parks, gardens, and urban forests, act as refuges for birds, insects, mammals, and plants in areas where natural habitats are scarce [78]. Green infrastructure in cities, such as interconnected parks, nature reserves, and green buildings, can significantly contribute to biodiversity conservation. For example, Singapore's extensive network of green spaces has been successful in preserving the city-state's rich biodiversity [79]. However, the concept of "artificial ecosystems" contributing to biodiversity conservation is not well-established in the research conducted to date. Urban green spaces aim to mimic natural ecosystems rather than create artificial ones [78]. While renewable energy systems for maritime applications and urban green spaces for biodiversity conservation are advancing, the integration of fusion power and the creation of artificial ecosystems for biodiversity are not currently realized.

Regarding technological advancements, our research has identified a number of these currently under exploration. While the ongoing focus on powering sustainable airports limited our consideration of these technologies, they have the clear potential to revolutionize many aspects of human life and society. While some of these may not be viable today, our backcasting process suggested the assumption of a future state and then an extrapolation of what technologies would be needed to reach that future state. The technologies suggested below are an extrapolation of today's trends to 50 years from now but could have major roles in a possible future state and in some case impacted our long-term scenarios.

1. **Fully autonomous vehicles** could revolutionize airport ground operations through integrated neural-network coordination, reducing terminal-to-aircraft transit times while enabling dynamic resource allocation that anticipates passenger needs before they arise.
2. **Smart Grid Power Transportation** may transform airports into energy-positive hubs through superconducting infrastructure with near-zero transmission loss, recovering aircraft braking energy and converting ambient vibrations from passenger movement into usable power.
3. **Advanced Additive Manufacturing** could enable on-demand creation of infrastructure components using programmable metamaterials. Airport runways might self-heal microfractures, while terminals may reconfigure to accommodate shifting passenger volumes.

4. **Artificial intelligence, genetic programming, and nanotechnology** will likely converge to create adaptive airport ecosystems evolving in response to usage patterns, with biologically-inspired approaches generating novel solutions beyond human conception.
5. **Orbital Manufacturing in microgravity** could establish supply chains between space-based facilities and major airport hubs, with materials impossible to fabricate under Earth's gravity potentially transforming airports into nodes in the Earth-space economy.
6. **Space tourism** may become a mainstream travel category with dedicated spaceport terminals. Pre-flight preparation could offer accelerated adaptation conditioning facilities, potentially making lunar or orbital getaways accessible to more passengers.
7. **Organoid computing** might process complex airport operations through synthetic neural tissues with exceptional efficiency. These wetware processors could optimize airport operations and other compute requirements while consuming minimal power, enabling sustainable computing at scale.
8. **Extended Reality and volumetric displays** will likely eliminate physical signage through persistent spatial computing environments. Customized informational overlays may transform blank terminal walls into personalized guides with real-time language translation and other guides.
9. **Circular economies** could transform airports into zero-waste systems where discarded items are immediately reprocessed and valued. Terminal furnishings might incorporate molecular markers allowing material separation, while water purification systems may extract valuable compounds for later reuse.
10. **Ocean thermal energy generation** might provide substantial power to coastal airports through advanced thermodynamic cycles. Deep-ocean cold water could cool terminal spaces directly, potentially reducing energy consumption while increasing passenger comfort.
11. **Nanoscale 3D printing** may revolutionize airport medical facilities through on-demand creation of patient-specific interventions, possibly enabling custom pharmaceuticals tailored to individual genetic profiles within minutes.
12. **Smart dust sensors** could form monitoring networks throughout airport facilities, constantly assessing structural integrity, air quality, and other indicators. Such sensor meshes might anticipate maintenance needs and identify potential health threats before symptoms appear.
13. **Digital twins** will enable airports to simulate operations with unprecedented fidelity. Computational models could predict passenger movements in advance, while personalized digital avatars or virtual assistants might identify potential congestion and help passengers before they arrive.
14. **Crypto-based markets** may transform airport economics through automated systems that optimize resource allocation in real-time. Dynamic pricing models for services, gates, and landing slots could maximize efficiency while ensuring equitable access.
15. **Quantum and photonic computing** will likely manage the complexity of global air traffic with profoundly precise capabilities. Weather prediction accurate to the minute and cubic kilometer might eliminate delays, while quantum encryption could secure communications against advanced threats.
16. **Urban and vertical farming** may integrate food production directly into airport structures, with specialized systems producing fresh ingredients daily. Genetically optimized plants could simultaneously filter air, produce nutrition, recycle waste and generate novel materials.
17. **Gene therapy and genetic engineering** might address travel-related health challenges through personalized interventions. Temporary genetic modifications could prevent jet lag, altitude sickness, and location-specific vulnerabilities through non-invasive delivery systems.

18. **Maglev vacuum trains** could connect major airport hubs through continental-scale transportation networks operating at hypersonic speeds, potentially enabling intercontinental transit in hours and transforming airports into integrated multi-modal nexus points.
19. **Human exploration of outer planets** may establish extraterrestrial airports as connection points to the solar system, with specialized terminals managing traffic to lunar bases and Martian facilities. Material harvested from asteroid mining could provide novel construction and in-situ resources.
20. **Food replicators** might replace traditional airport dining through molecular gastronomy systems capable of recreating dishes from basic nutrient stocks, potentially eliminating food waste while providing nutritional customization based on individual traveler needs or preferences.
21. **Nanobots connecting brains to the cloud** could transform passenger experience through consensual neural interfaces providing instantaneous information and translation. Temporary neural augmentation might enable intuitive navigation with quantum-secured privacy protocols.
22. **Space-based solar arrays** may provide airports with power generation capacity immune to terrestrial conditions. Orbital photovoltaic fields could transmit power to receiving stations integrated into airport infrastructure, potentially eliminating fossil fuel dependency.

Further, certain technological advancements are considered paradigm-shifting for humanity due to their potential to fundamentally transform various aspects of our society and existence. Again, while not fully vetted, occurrence of any one of those listed must be considered and are therefore included in our findings.

1. **Artificial General Intelligence (AGI)** could represent a cognitive breakthrough enabling systems that match or exceed human reasoning across all intellectual domains. AGI might autonomously advance scientific knowledge, optimize global resource allocation, and design even more advanced successors, fundamentally altering humanity's relationship with technology and labor.
2. **Gravity Modification (GEM Unification Theory)** may enable controlled manipulation of spacetime through unified electromagnetic-gravitational field interactions. Such capability could transform aerospace design by eliminating traditional propulsion limitations, potentially making interstellar travel feasible and opening unprecedented energy harvesting opportunities from gravitational potential.
3. **Ambient Temperature & Pressure Superconducting Materials** would likely revolutionize global energy systems by enabling lossless power transmission across continental distances. These materials might lead to compact fusion reactors, frictionless transport systems, and quantum computing architectures operating at room temperature with dramatically reduced resource requirements.
4. **Bipedal Autonomous Robots** could fundamentally reshape economic systems through universally adaptable physical labor platforms. These systems may navigate human-designed environments without modification, perform complex physical tasks with minimal supervision, and potentially serve as embodied extensions of human consciousness in hazardous or remote environments.
5. **Discovery of other life elsewhere in the solar system or beyond** could represent a profound philosophical and scientific inflection point potentially altering humanity's self-perception and our understanding of life at a more general level. Such discovery might provide evolutionary insights revealing alternative biochemistries, novel technological approaches derived from non-human resource utilization, intelligence or information-processing.

However, it should be noted that there is a vast array of unexpected catastrophic events beyond those we considered associated with global temperature change. Such catastrophic events would also have significant impact on humanity changing the scenarios below but are not considered in this study.

Future Scenarios

Based on the core understanding of the available power alternatives, three different scenarios were examined to understand future PESTEL pathways as illustrated in Figure 9. Specifically, the following scenarios represent distinctly different visions of airport operations in 2075, each shaped by varying assumptions about technological progress, climate impacts, and societal adaptation. These futures were developed using backcasting methodology, i.e., working backward from 2075 to identify the critical developments and decision points that could lead to each outcome combined with forecasting for the next ~25 years. While all three scenarios acknowledge the fundamental role of global temperature change, they diverge significantly on its impact and in how humanity responds to this challenge. It should be noted that these scenarios are meant to examine differing extents of change to the present status quo with increasingly severe consequences.

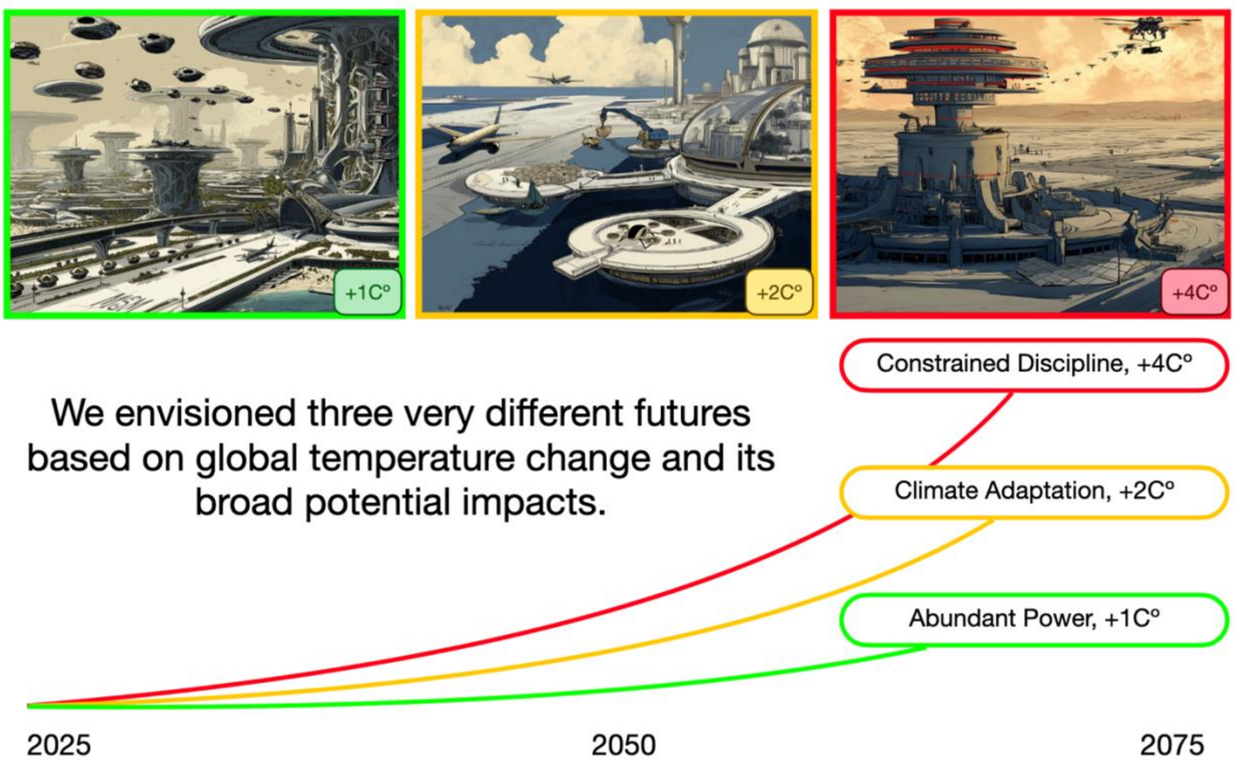

Figure 9 The 3 Different Scenarios Envisioned in this Study

In the Abundant Power scenario (#1), technological breakthroughs—particularly in fusion energy and hydrogen infrastructure—enable a transformative future where airports become mega-hubs of innovation and sustainable development. The Climate Adaptation scenario (#2) envisions airports fundamentally reshaped by environmental changes, with floating and submersible structures adapting to rising sea levels and extreme weather events. Finally, the Constrained Discipline scenario (#3) depicts a more austere future, where a 4°C temperature rise forces airports to operate under strict resource limitations, transforming them into heavily regulated nodes primarily serving essential travel and climate refugee coordination.

The various temperature changes for the scenarios are notional and generally represent different outcomes envisioned with increasing environmental impact. The temperature changes of 1, 2 and 4 °C are meant to be reflective of the impact of an increasing severity of global atmospheric warming, moving from a near ideal abundant state towards an austere resource limited world, rather than predictions of the impact of exact numerical values of global temperature change. It is important to note that many of the aspects of these future states are only hypothetical and these values are intended to define a conceptual world to generate thought, not to provide rigorously calculated numerical benchmarks. The technologies and concepts referred to below are generally discussed above in the Significant Future Trends and Technologies section. Any numerical estimates provided below, such as 90% renewable energy usage, are notional and generated in this backcasting process as to what would be needed to reach this future reality. As noted in Section II.I, other scenarios could be considered based on a different range of positive or negative assumptions; this work assumes three complementary scenarios of increasing global atmospheric warming and uses these frameworks to examine potential future states.

Scenario 1: Abundant Power Scenario

By 2075, the Abundant Power Scenario envisions a transformation-driven future mega-hub airport that exemplifies a world reshaped by multiple parallel energy innovations. This future is built on four key technological pillars that develop in parallel: advanced solar power systems, interim SAFs, commercially viable fusion, and mature hydrogen infrastructure. The transformation-driven future mega-hub airport exemplifies a world where radical innovations and profound changes redefine every aspect of living, working, and interacting. This vision showcases an airport that seamlessly integrates emerging technologies, fosters a universal admixture of international cultures and neurodiverse inclusivity, and embraces new paradigms of sustainability, mobility, energy, and biotechnological advancements. With fusion energy now viable and a mature hydrogen infrastructure having been proven and tested for decades, this airport operates as a beacon of immense energy potential, environmental stewardship and highly iterative transformations. An illustration of this scenario is shown in Figure 10 and the key technologies with various societal, economic, and environmental impacts and consideration are described below.

Figure 10: Envisioned Abundant Power Scenario (#1) Shown is transformation-driven future mega-hub airport featuring multiple modes of transportation with abundant power coming from an array of sources.

In general, parallel advances across a series of PESTEL fields, especially a range of technology development, have resulted in a desirable future where many of the most severe impacts of global temperature change have been avoided and the foundation for a sustainable future has been established. Aspects of this Abundant Power scenario include:

- Key Technologies: This future airport integrates multiple complementary energy sources: space-based solar power arrays, fusion power plants providing most base power needs, hydrogen infrastructure serving as both fuel and energy storage, and SAF adoption for remaining aviation needs. Quantum computing powers advanced operations, while supersonic and hypersonic travel redefine long-distance transportation. Biotechnology and nanotechnology are seamlessly integrated into airport infrastructure, enabling adaptive and self-repairing systems.
- Societal and Economic Impacts: The airport fosters a universal admixture of international cultures and neurodiverse inclusivity, becoming a nexus for global economic activity and cultural exchange. It operates as a multimodal transport hub, connecting air, land, and potentially space travel. The abundance of clean energy drives economic growth and technological innovation, reshaping job markets and skill requirements.
- Environmental Considerations: Leveraging fusion power and a circular economy approach, the airport achieves beyond net-zero emissions, actively contributing to environmental regeneration and carbon sequestration. Fusion-powered desalination plants address water scarcity, while advanced resource management systems eliminate waste, turning all byproducts into valuable resources.
- Challenges and Adaptations: Despite the abundance of energy and technological advancements, the airport faces challenges in managing the rapid pace of change. Cybersecurity concerns are paramount given the highly interconnected systems. Ethical considerations around AI decision-making and data privacy require ongoing attention and awareness of a need for exceptions. The airport continuously adapts its infrastructure and services to accommodate emerging technologies and changing societal needs, emphasizing flexibility and futureproofing in all its designs.
- Energy Integration: The airport serves as a demonstration site for the successful integration of multiple sustainable energy sources, with each playing a specific role: fusion for baseline power, solar for peak demand, hydrogen for storage and fuel, and SAFs for specialized aviation needs. This diverse energy ecosystem ensures resilience while maintaining zero emissions.

The pathway to a future of Abundant Power future state is envisioned across the decades as follows:

1) The foundation is established in 2030 with parallel developments across multiple sectors. Solar power installations begin on rooftops, fields, and walkways at airports, maximizing horizontal space and acreage utilization. The first key tests of H_2-powered aircraft prove successful, while SAFs achieve complete interoperability with Jet-A fuel. Airports implement comprehensive energy management systems that enable integration of these diverse power sources, marking their evolution into regional innovation hubs.
2) By 2040, significant technological milestones reshape airport operations. Solar panel recycling becomes commonplace, while regional aviation and certification processes for transferring new hydrogen fuel technologies are established. SAFs reach cost parity with conventional jet fuel. Small modular fission reactors (SMRs) begin commercialization,

laying groundwork for highly distributed nuclear power integration. These developments coincide with airports' transformation into multimodal transport hubs.

3) The 2050 milestone sees fusion technology reaching maturity, with the first commercial fusion reactors becoming operational and providing 25% of U.S. power. Hydrogen establishes itself as an export commodity, while electrolysis efficiency improvements reduce water demand. The electrical grid must be significantly rebuilt to handle extreme weather events, highlighting airports' critical role in regional resilience. Global air labor standards are established for the aviation industry.
4) By 2060, first nuclear-powered aircraft take flight as fusion powerplant prices service becomes widespread. Hydrogen infrastructure achieves comprehensive connectivity of energy infrastructure, while nuclear power becomes a substantial power source. International flight operations achieve 90% renewable energy usage, marking a decisive shift away from fossil fuels.
5) The 2070 period sees airports become powered entirely by clean, sustainable fusion energy. This is complemented through space-based solar power from low earth orbit (LEO) stations. Hydrogen fuel cells enable longer range flights while cutting operational costs by 25%. Space-based solar arrays and orbital power stations provide additional renewable energy capacity.
6) By 2075, the transformation culminates in airports powered by multiple complementary sustainable technologies: space-and-surface-based solar arrays verify stream power generation, hydrogen becomes standard for all aerospace systems, and SAFs are completely replaced by carbon-zero, non-combustion options.

Examples of the progression in the various PESTEL fields across the decades is provided in Figure 14 and Figure 15 in Appendix B for the of Abundant Power scenario. These figures examine this scenario's decadal evolution through the lens of various "Swim lanes" that include various forms of power generation, fuels usage, and energy transfer and storage, as well as socioeconomic, policy and legal, and considerations. Note that we use the term "swim lanes" to help guide the reader in following the path or 'lane' that a given topic moves and evolves. This evolution is a combination of forecasting and backcasting where some benchmarks/drivers are suggested from forecasting while others are generated from backcasting expanding on published speculations related to the evolution of the given field.

Scenario 2: Climate Adaptation Scenario

By 2075, the Climate Adaptation Scenario presents a world fundamentally reshaped by global temperature change, where adaptation and resilience have become paramount in a global population of 11 billion. The world has changed. Global temperature change has caused significant portions of coastal lands to be either impacted or underwater. This includes impact to significant airports that presently serve as major hubs. Society responds with resilience, adaptability, and autonomy. The technology developed in the abundant scenario by 2050 is available, and it is these technologies that are used to provide an adaptable airport future despite vastly changed ecological conditions. Airports in some locations are on the water but seamlessly connected with hyperloops and small air transport, revolutionizing ground transportation and enhancing connectivity and efficiency. Other airports operate while adapting to frequent extreme weather events. Airports benefit from highly efficient carbon capture and zero-waste circular operations in stores and restaurants. Airports evolve from traditional transportation hubs into climate-resilient mega-structures while adapting to extreme environmental challenges.

Figure 11: Envisioned Climate Adaption Future State (#2) Shown is an airport system responding to changes resulting from global temperature change with resilience, adaptability, and autonomy.

An illustration of this scenario is shown in Figure 11, and the key technologies with the various societal, economic, and environmental impacts and consideration are described below. Aspects of this Climate Adaption Future State include:

- Key Technologies: In response to rising sea levels and environmental shifts, airports have evolved into resilient, water-adaptive hubs utilizing biomimetic self-repairing materials and floating infrastructure capable of handling 70% of global passenger activities. Advanced nanoscale assembly systems operate in hostile environments, while quantum encryption complements critical infrastructure. Photonic computing manages 30% of operations through passive robotics, complemented by AI-integrated electrical grids with advanced flood management systems processing 20,000 ft^3/day. These technologies enable airports to maintain operations under extreme climate conditions while supporting essential community functions.
- Societal and Economic Impacts: The transformation of coastal regions has fundamentally altered airport operations, with 45% of airport space now adapted for non-flight activities. Coastal security and operational systems have become integral to airport management, as have wildlife preservation zones and climate refugee support facilities. The transition to autonomous flight systems handling 40% of air traffic, combined with carbon credit systems reaching 600,000 credits/ton, has reshaped both aviation economics and social patterns. Airports have become critical nodes of climate-resilient infrastructure, serving as the core of new, adaptive urban developments.
- Environmental Considerations: These future-proof airports are designed to work in harmony with their altered environments, incorporating on-site CO_2 capture plants processing 1000 tons annually per major facility. Complete water recycling systems and tritium harvesting capabilities demonstrate advanced water management, while multiple SAF methods and hydrogen fuel systems achieve cost parity with traditional fuels. Energy systems combine solar, wind, maritime and limited fusion power, achieving energy gain factors of 50, while extensive green spaces and artificial ecosystems contribute to biodiversity conservation.
- Challenges and Adaptations: With at least 50% of coastal airports utilizing some amphibian or floating infrastructure, the constant threat of extreme weather events requires continuous innovation in airport design and operations. Advanced drainage systems, integrated waste compression, and modified air traffic patterns accounting for increasing risks from space debris (generated by the Kessler effect [80-82]), represent ongoing adaptations. Hybrid hydrogen powerplant flights and enhanced UV protection systems for passenger safety demonstrate the complex balance between maintaining

global air routes and ensuring operational resilience. Despite these challenges, these adaptive airports stand as beacons of human ingenuity in the face of drastic environmental change.

- Energy Integration: The airport integrates multiple adaptive energy systems, combining solar-powered aircraft capabilities and distributed generation through regulated solar panels and runway wind turbines. Hydrogen infrastructure achieves cost parity with conventional fuels, ultimately replacing 90% of SAF usage. Fusion power plants and tritium harvesting provide baseline power, supplemented by comprehensive micro-generation systems. These include thermodynamic, acoustic, piezoelectric, and magnetocaloric energy recovery, along with advanced carbon capture processes. AI-managed smart grids enable dynamic load balancing across these diverse sources while ensuring adaptability to meet extreme weather events.

The pathway to a future of Climate Adaptation future state is envisioned across the decades as follows:

1) The 2030s mark the beginning of fundamental changes in airport operations. Automation and robot economy directly affects 13% of all airport professions. Solar power becomes regulated in airport areas with 50% of new airport contracts including sustainability clauses. Hydrogen fueling infrastructure begins development, while groundbreaking Maglev train systems commence development. European airlines pioneer short-duration SAF, electric and hydrogen-powered flights.
2) By 2040, biotic materials that self-repair become standard in airport design, while 1000 tons of CO_2 are captured annually per major airport through on-site capture plants. Notably, 30% of airport operations are managed by photonic computing systems and passive robotic UAS. Hydrogen-powered flights become operational under 2 hours, while 35% of airports adopt standalone waste compression tanks.
3) The 2050s usher in floating airport development projects targeting a notable rise in passenger capacity. Airports fully recycle grey water and incorporate AI-driven electrical grids. Draining systems on runways for floods increase capacity to 20,000 ft^3/day. New forms of hydrogen fuel cells and multiple other power methods become standard, while fusion pilot plants begin to emerge.
4) The 2060s see 45% of airport space adopted by non-flight activities as operations become more efficient. Space and aviation laws are completely rewritten to adapt to changing technologies. The Kessler effect stops 20% of space travel, pushing more traffic to advanced aerial routes, with carbon costs increasing from 250,000 to 600,000 credits/ton.
5) By 2070, coastal guard becomes a vital part of airport security, and hydrogen becomes cost-competitive with jet fuel. Airports double as wildlife preserves, and floating airport test sites become fully operational. Tritium harvesting from water is achieved, while 30% of coastal airports begin to incorporate "floating tech."
6) The scenario culminates in 2075 with mega-hub services achieving 70% of all global passenger activities. Global population stabilizes at about 11 billion, while fusion energy gain factors increase to 50. Notably, 50% of coastal airports utilize floating infrastructure, 40% of flights become autonomous, and advanced nanoscale assembly systems begin operating even in hostile high-temperature environments.

Examples of the progression in the various PESTEL fields (Swim lanes) across the decades is provided in Figure 16 for the Climate Adaptation scenario. A core feature of this scenario is that the technology development achieved up until the year 2050 in the Abundant Power scenario is still assumed to be available in the climate adaptation scenario. Those technologies are not reproduced in Figure 16, but only the differences between these two scenarios. Nonetheless, it is these technologies that are repurposed to allow adaptation to a significantly changed world as a result of global temperature change.

Scenario 3: Constrained Discipline Scenario

By 2075, the Constrained Discipline Scenario depicts a world grappling with the severe consequences of a 4°C global temperature rise, where resource scarcity and strict environmental controls fundamentally reshape aviation into a necessity-based system. By 2075, the effects of 4°C global temperature change has limited technology development and strongly impacted the nature of travel. Air travel is not a convenience, but on "need to basis". Airports optimize operations to promote sustainability, with strict energy budgets and controlled, or marginal cost pricing. Government policies limit consumption and curtail domestic flights under two hours, encouraging multi-modal travel and reducing environmental impact. Bio-implants and advanced AI technologies personalize the airport experience monitoring the passengers, while stringent energy usage policies lead to the shutdown of under-utilized airport areas. Airport infrastructure has vastly changed to accommodate a volatile and world of limited resources. Some unhospitable regions have limited air travel but are, nonetheless, places in which commerce, power and transportation merge.

An illustration of this scenario is shown in Figure 12 and the various societal, economic, and environmental impacts and consideration are described below. Aspects of this Constrained Discipline Future State include:

Figure 12: Envisioned Constrained Discipline Scenario (#3) Shown is an airport system where resource scarcity and strict environmental controls fundamentally reshape aviation into a necessity-based system.

- Key Technologies: Despite material and energy constraints, airports deploy sophisticated management systems including AI/VR interfaces for personalized passenger experiences and quantum simulation systems detecting 99.9% of extreme events. Personal bio-implants integrate with security systems, while lasers and synthetic biology applications maintain critical infrastructure. Increased UV index in the atmosphere is leveraged for airport waste sterilization, while drones and UAVs handle certain operations. Airport cargo shipping flights become fully autonomous, with quantum control systems enabling precise management under extreme resource constraints. These adaptations allow continued operations despite severe impacts of global temperature change on airport operations and scarcity of available resources.
- Societal and Economic Impacts: Air travel transforms into a heavily regulated necessity-based system, with access determined by social sustainability credits for minimizing climate impact and priorities determined by government bodies. Commercial airports begin diversifying revenue streams by prioritizing cargo transport,

with main airport travel compressed to cargo shipping and essential travel only. All facilities become slot-controlled with strict limits on air traffic and airspace usage. The displacement of over 1 billion climate refugees reshapes airport operations, while international laws governing aviation ethics adapt to manage scarce resources. US Coast Guard deployment at airports reflects increased security pressures.

- Environmental Considerations: Strict sustainability measures govern operations, with 5% Compound Annual Growth Rate (CAGR) for all passengers and most airports achieving SEMA (Sustainable Environmental Management Accreditation) status. Bio-regenerative measures reduce heat island effects by 30%, while quantum monitoring systems enable precise environmental control. Airports maintain biomimetic design principles planned with a nature compatible mentality while incorporating advanced cleaning technologies to combat environmental degradation as well as increased bacterial and viral threats.
- Challenges and Adaptations: Rising energy costs and material scarcity force airports to rely on synthetic alternatives, with 90% of small plane airports closing due to operational pressures. The American Southwest becomes largely unsuitable for aviation, while coastal airports require extensive floating infrastructure. Travel credits linked to fossil fuel usage accumulate, optimize, and limit travel, as private flights are heavily restricted.
- Energy Integration: Material scarcity fundamentally reshapes energy systems, forcing reliance on limited (if any) fusion alongside advanced recovery systems. Infrastructure innovations maximize efficiency of remaining fossil resources, while quantum-enabled grid management ensures optimal distribution of scarce power. Microfinance and microgrid energy programs support climate refugee needs while maintaining essential power systems. The electrical grid evolves to become more resilient against extreme weather events, though with significantly reduced capacity compared to the other two scenarios (above).

The pathway to a future of Constrained Discipline future state is envisioned across the decades as follows:

1) The 2030s mark the fundamental shift toward restricted air travel. Commercial airports begin diversifying revenue streams through cargo transport. AI/VR interfaces are created to personalize passenger experience while reducing space and travel demands. Material scarcity limits energy generation, requiring strict material recovery and recycling. Virtual queuing systems decrease wait times, while flights under 2 hours in length are banned as infrastructure improves to make alternative transport viable.
2) The 2040s see increased restrictions and adaptations. Subsidies for green technologies increase implementation by 50%, while neural interfaces and wearable computing (sometimes including bio-implants) enable enhanced security and overall operations. 90% of small plane airports close due to mounting flying costs, and SAF production shifts downward due to inadequate fertilized land. Global North aims to limit CO_2 emissions to match Global South levels, while train and road infrastructure expands to account for the lack of short-haul flights.
3) By the 2050s, the 5% CAGR limit for all air passengers becomes standard. International laws governing suborbital flights limit transit options, while the Southwest becomes largely deserted for air travel. Neural interfaces and wearable computing create personalized passenger experiences, and increased UV index is used to sterilize airport waste. Drones and UAVs are incorporated into logistics to reduce carbon-intensive operations.
4) The 2060s brings further constraints. US Coast Guard deployment to airports coincides with the transition to complete slot-controlled operations, while over one billion climate refugees have been displaced. The implementation of internationally ratified aviation

ethics agreements becomes crucial for managing unprecedented passenger flows and security challenges. The electrical grid system is hardened to become more resilient against extreme weather events, while aircraft carriers begin serving as mobile airports for many different vehicles to provide flexible infrastructure in an increasingly unstable environment with reduced power availability.

5) By 2070, lasers and biomimetic innovations are incorporated into airports for cleaning purposes, while social sustainability credits determine who has access to travel amenities. Airports use selective sourcing and bio-regenerative measures to reduce heat island effects (i.e., deploying extensive living architecture systems that actively cool surrounding microclimates through evapotranspiration and reflective surfaces) by 30%. Airport shipping flights become mainly autonomously piloted further reducing costs and inefficiencies.
6) The transformation continues in 2075 with immigration laws becoming increasingly restrictive as conditions worsen. Quantum control systems detect 99.9% of extreme events at 200km range, while bioengineering begins deep impact efforts to reverse damage of the previous decades. Space, subterranean, and submarine settlements emerge as a potential necessity rather than luxury, or experiment, as Earth-based aviation continues to operate under increasingly severe constraints.

Examples of the progression in the various PESTEL fields (Swim lanes) across the decades are provided in Figure 17 below for the of Climate Adaptation scenario in Appendix B. A core feature of this scenario is technology development seen in the Abundant Power scenario #1 which alters the scenarios in conjunction with the impacts of global temperature change. This redirects technology development towards a response to scarcity and extreme weather events as well as individual and social control.

Pivot Points

A pivot point represents a crucial junction in technological evolution that significantly shapes and enables future technological developments. Such a juncture has profound impacts, including opening multiple options for future states, eliminating risks associated with technological barriers, and enabling the emergence of new capabilities, industries, and technologies. Historical examples of pivot points include the first flight at Kitty Hawk by the Wright brothers, the development of the semiconductor, and the introduction of the first smartphones—each marking not just a singular achievement but catalyzing cascading innovations across multiple industries.

In the context of future airport energy systems, the timeline reveals critical pivot points that could determine which of our three scenarios—Abundant Power, Climate Adaptation, or Constrained Discipline—becomes dominant.

Figure 13 shows the Pivot Point timeline for the Abundant Power scenario which features the most amount of positive change. The progression from AI and quantum technologies in 2035 to large-scale sustainability implementation in 2040 establishes the foundational infrastructure necessary for the more optimistic scenarios. By 2045, the development of highly efficient power distribution systems complemented by renewable integration becomes a decisive moment—success here could enable the Abundant Power scenario, while limitations could push toward the Constrained Discipline scenario.

The 2050-2055 period emerges as particularly crucial, where the convergence of autonomous systems and hydrogen economy installation could determine the feasibility of large-scale adaptation. The establishment of fusion power plants by 2060 represents perhaps the most significant pivot point, as success or failure in this technology could dramatically influence whether we achieve the abundant energy future or must adapt to severe constraints.

The final pivot point in 2070, featuring nanotech assemblers and widespread hydrogen adoption, could ultimately determine whether airports evolve into the envisioned mega-hubs of the Abundant Power scenario or the more restricted, necessity-based facilities of the Constrained Discipline scenario.

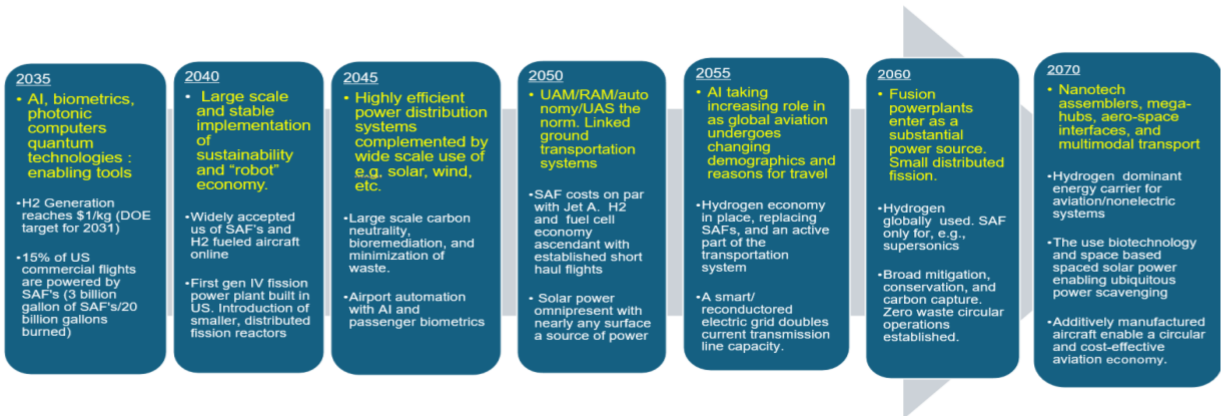

Figure 13: Pivot Point Timeline for the Abundant Power Scenario

Abundant Energy Technology Timeline

The Abundant Energy scenario is both the most optimistic scenario and the scenario that includes the largest quantity of successful technology development. Figure 13 provides a broad vision of significant steps (pivot points) necessary to achieve the Abundant Energy scenario. However, to enable such a transition to abundant clean energy by 2075 requires significant technology development especially in energy technologies. Figure 18, the Abundant Energy timeline in Appendix C, provides in expanded detail some of the steps necessary to achieve this vision. This Abundant Energy timeline maps the evolution and convergence of three critical technological tracks that enable a transition to abundant clean energy by 2075. Each track represents a distinct but interdependent pathway toward sustainable aviation and are described below.

In electricity generation, the progression begins with local pilot programs achieving critical early milestones, including increasing solar panel efficiencies by 2030. Nuclear power development accelerates through the 2040s, with nuclear power plants providing ~25% of US power, while next-generation distributed energy systems improve reliability. The transition to fusion power marks a crucial shift between 2050-2060, as nuclear becomes more cost-effective and evolves into the dominant energy source. By 2075, fusion power plants achieve the goal of providing cost-competitive energy services, representing a fundamental transformation in base power generation capability.

The energy transfer and storage track demonstrate the crucial developments in infrastructure needed to support this energy transition. Beginning with pilot-scale storage facilities, the timeline shows progression through increasingly sophisticated grid management systems. Particular attention is paid to increases in power transfer and storage efficiency, with significant breakthroughs in electrical grid capacity to handle massive renewable loads. The development of integrated smart grid systems becomes essential for managing the complex mix of fusion, solar, and other renewable sources.

Perhaps most significantly for aviation, the vehicle propulsion track charts the complex transition from conventional to sustainable aircraft systems. The timeline begins with hydrogen applications and fuel cell pilot programs, progressing through widespread SAF implementation. By mid-century, aircraft modifications enable zero-emission flight, while the latter decades see the emergence of fusion-native propulsion systems. This revolutionary development in propulsion technology aligns with the maturation of fusion power generation, creating a synergistic relationship between power source and vehicle technology.

The timeline notably illustrates how advancements in one track enable or require developments in others. For instance, the evolution of fusion power generation is most impactful when corresponding improvements in energy transfer systems, while also enabling new possibilities in vehicle propulsion. By 2075, these three tracks converge to create a fully integrated, sustainable aviation energy ecosystem where abundant clean power becomes not just available but economically advantageous.

Challenges and Threats

Airports are currently grappling with a myriad of challenges in integrating cutting-edge technologies and sustainable practices while safeguarding against emerging threats that could stall or even reverse progress towards a more sustainable future. For progress to be made towards a sustainable aviation future, understanding the potential challenges and threats associated with this optimistic view is warranted, and technological evolution is one of the first steps towards being able to mitigate possible future risks. The following discussion assumes broad-based technology development of the Abundant Power scenario but also examines potential impediments to that development.

One of the primary concerns centers around cybersecurity vulnerabilities and privacy issues posed by the increasing adoption of AI and robotics, biometrics, neural interfaces, and quantum communications. These innovations, while enhancing operational efficiency, introduce significant risks including quantum-enabled attacks against AI systems, biometric data breaches affecting automated passenger processing, and virtual travel system compromises. The uneven adoption of these technologies across different airports and associated infrastructures creates security gaps and expands potential attack surfaces, particularly in integrated energy management systems.

Regulatory frameworks struggle to keep pace with rapid advancements in multimodal transportation and energy integration, leading to potential misalignments between social, political, and economic priorities. This lag hinders the widespread implementation of SAF and hydrogen infrastructure, which already faces obstacles like storage and production capacity limitations, and supply chain vulnerabilities. Introduction of new vehicle types into the airspace, including autonomous vehicles to small drones, and space ferrying vehicles, will necessitate both customer and regulatory acceptance. Future new technologies not presently available commercially will also face significant regulatory framework challenges. For example, the emergence of biotic materials and nano-scale maintenance systems introduce new environmental and security concerns, particularly regarding their potential weaponization or unintended ecological impacts.

The challenges extend to power grid vulnerabilities as multiple energy sources—including localized renewable energy, hydrogen systems, and prospective fusion power—become increasingly interconnected. This complexity is compounded by the risk of technological stagnation in critical areas like fusion development due to resource constraints, security, and resistance from entrenched interests. Global temperature change poses additional threats by stressing infrastructure resilience, particularly for coastal facilities and southern latitudes, while advanced transportation systems risk exacerbating social inequalities and sparking broader socio-economic conflicts.

Moreover, the integration of air and space traffic introduces novel hazards, particularly regarding space-based manufacturing centers, power transmission systems, and cohabitation of both air and space launch systems. The abundance of future energy systems could paradoxically lead to misuse and environmental degradation if not properly managed. Airports must therefore navigate these multi-faceted threats while developing adaptive, forward-thinking strategies to ensure resilient and sustainable evolution in aviation and transportation.

Two critical threat vectors merit rigorous investigation from thermodynamic and resource availability perspectives. First, the widespread deployment of high-density power sources, such as distributed fusion reactors—potentially scaling to household-level implementation—raises concerns about cumulative thermal loading on Earth's systems. If a world of abundant power is reached, then we may also see a world of abundant heat generation. For example, while fusion power is clean from an emissions standpoint, the aggregate heat production from many large and/or small-scale reactors could alter local and regional thermal gradients, potentially disrupting atmospheric circulation patterns and exacerbating urban heat island effects. In accordance with the Second Law of Thermodynamics, all energy ultimately degrades to heat, requiring that this thermal energy be dissipated into environmental sinks. This raises fundamental questions about potential planetary thermal imbalances when fusion deployment achieves widespread implementation, as heat rejection at such scales may exceed local environmental absorption capacity. Second, global temperature change-induced alterations to the hydrological cycle threaten hydrogen production capacity. Accelerated evaporation rates, disrupted precipitation patterns, and increasingly frequent extreme weather events could significantly impact water availability for electrolysis processes. Current models may underestimate the feedback loop between rising temperatures and water cycle intensification, potentially compromising the water-intensive hydrogen production infrastructure. These intersecting challenges elucidate the need for sophisticated modeling of both thermodynamic boundaries and water resource availability in future energy scenarios.

In the context of the Abundant Power future in Scenario #1, airports face immediate challenges in integrating new technologies and sustainable practices. The rapid adoption of AI and biometrics introduces cybersecurity risks and privacy concerns. SAF implementation is hindered by supply chain and production capacity limitations. Uneven technology adoption across airports creates security and efficiency gaps. Power grid vulnerabilities emerge as multiple energy sources are integrated. Localized renewable energy sources struggle to complement larger power systems effectively. These challenges are compounded by potential misalignment between social, political, and economic factors and sustainable aviation goals, potentially slowing progress in this optimistic scenario. The low level threats listed below are immediate challenges visible in the next ten years, such as integrating sustainable fuels and optimizing ground operations, and include:

Low Level Threats (from Future Scenario 1: “Abundant Power”):

- **AI-driven security vulnerabilities**, such as adversarial attacks that could manipulate autonomous baggage handling systems or compromise predictive maintenance algorithms, creating both safety and operational risks.
- **Biometric data breaches**, i.e., unauthorized access to centralized repositories of passenger biometric identifiers that could enable identity theft at unprecedented scale or targeted surveillance of high-profile travelers.
- **Regional airport technology shortfalls**, creating a two-tier aviation system where smaller facilities lack the capital resources to implement advanced security protocols or, for another example, energy management systems.
- **Power grid vulnerabilities**, especially at interface points between traditional infrastructure and new high-density energy storage systems, where cascading failures could propagate.
- **Localized power source limitations**, particularly during extreme weather events, when distributed renewable generation may be compromised across multiple micro-grid systems.

- **Socio-political-economic misalignment**, manifesting in regulatory fragmentation across jurisdictions that creates compliance challenges for international carriers and impedes standardization of emerging technologies.

In the mid-term future of Scenario 1, airports face increasingly complex challenges as they evolve with abundant power and advanced technologies. These threats highlight the complexities of integrating quantum communications and AI-driven operations. The reliance on new materials and energy sources introduces vulnerabilities in supply chains and potential environmental impacts. Regulatory frameworks struggle to keep pace with rapid technological advancements, particularly in multimodal transportation and energy integration. As systems become more interconnected, cybersecurity risks increase exponentially. The balance between energy demand and supply remains precarious, with risks of technological progress slowing due to entrenched interests or resistance to change. The mid level threats listed below are emerging issues on the 10- to 30-year horizon, including adapting to climate impacts and implementing advanced automation. They include:

Mid Level Threats (from Future Scenario 1: "Abundant Power")

- **Quantum communication infrastructure attacks**, potentially leveraging still-undiscovered vulnerabilities in post-quantum encryption protocols that could compromise the integrity of global air traffic management systems or enable sophisticated state-sponsored surveillance.
- **AI decision-making in operations**, where emergent behaviors in complex adaptive systems might prioritize efficiency over human safety considerations in ways difficult to predict, especially during cascading fail scenarios.
- **Advanced materials supply chain disruption**, particularly for critical components relying on rare earth elements or engineered materials that face geopolitical resource constraints or manufacturing bottlenecks.
- **Regulatory lag in multimodal or multi-fuel integration**, creation of governance gaps in which emerging transportation interfaces between hypersonic ground systems, conventional aviation, and orbital operations lack coherent safety frameworks or interoperability.
- **Ecosystem impact of distributed energy generation**, where cumulative effects of widespread deployment create unforeseen consequences for biodiversity and ecosystem services, such as disrupted migration patterns from extensive solar arrays or altered microclimate conditions near fusion operations.
- **Cybersecurity gaps in interoperable systems**, arising when legacy infrastructure interfaces with next-gen technologies through imperfectly secured protocols, creating exploitation vectors.
- **Energy demand-supply imbalance**, where abundant but intermittent power generation creates temporal mismatches between airport requirements and available energy, necessitating massive storage systems vulnerable to coordinated attacks or other technical disruptions.
- **Technological stagnation**, resulting from consolidation among key technology providers or IP regimes that manufacture or invent bottlenecks, potentially locking airports into sub-optimal technological pathways creating prohibitive switching or improvement costs.

In the long-term outlook of Scenario 1, airports face complex challenges that intersect with broader societal and technological issues. The potential stagnation or failure of fusion energy development could leave the aviation industry vulnerable. Global temperature change poses increasing threats to infrastructure resilience. Advanced transportation systems risk exacerbating social inequalities. Emerging biosecurity risks, including engineered pathogens and tech-bio convergence, introduce novel risks, especially for high-traffic hubs. The integration of air and space traffic introduces unprecedented hazards. Paradoxically, the abundance of energy envisioned in this scenario could lead to unforeseen multi-order risks and environmental degradation if not managed responsibly. The high level threats listed below are long-term, transformative challenges beyond 30 years, such as quantum and adapting to potential off-world settlements. They include:

High Level Threats (from Future Scenario 1: "Abundant Power")

- **Fusion energy development stagnation**, where persistent engineering challenges create insurmountable barriers to commercial viability, potentially stranding infrastructure investments and forcing rapid recommitment to alternative and potentially faulty or under-developed energy pathways.
- **Global temperature change-induced infrastructure stress**, manifesting in accelerated material degradation of runways from thermal expansion cycling, increased flooding, and disruption of critical navigation systems due to atmospheric turbulence that exceed design parameters.
- **Socioeconomic conflict due to advanced transit**, whereby travel and tourism become exclusively costly domains, creating two-tiered mobility rights that exacerbate existing inequalities and potentially trigger sociopolitical conflict.
- **Bioengineered pathogen risks**, particularly at international hub airports that could serve as amplification points for engineered infectious agents designed to evade conventional detection systems.
- **Space debris impact on air-space integration**, in which proliferating orbital debris fields create unpredictable reentry hazards, requiring airspace closure and trajectory prediction capabilities.
- **Synergistic tech-bio threats**, emerging from the convergence of synthetic biology with advanced computing systems that could enable self-modifying biological agents capable of targeting specific populations or disrupting critical airport operations.
- **Small scale reactor unattainability**, where anticipated miniaturization of fusion systems fails to materialize, leaving airports dependent on centralized power generation and limiting the development of independent terminal operations.
- **Energy abundance abuse**, in which resource-intensive passenger amenities and operational redundancies squander designed efficiency benefits of advanced power systems, creating unsustainable thermal loading and undermining broader sustainability objectives.

Key Findings and Research Opportunities

The key findings we describe below represent critical insights derived from our analysis of future airport energy scenarios, particularly focusing on the three notional scenarios we explored: Abundant Power, Climate Adaptation, and Constrained Discipline. Through a backcasting methodology, we identified patterns, correlations, and causal relationships that emerged consistently across multiple future states. This process involved defining desired and probable 2075 conditions, then working backward to identify the necessary technological developments, policy frameworks, and societal shifts required to achieve or adapt to these conditions.

The findings are organized into three categories: "Prevalent" findings that address overarching themes of technological convergence and societal transformation; "Significant" findings that detail specific technical and operational requirements; and "Surprising" findings that highlight unexpected challenges and opportunities. Through iterative analysis, we identified critical measures and decision points that appear consistently across different scenarios, providing insights into resilient and sustainable pathways for airport energy systems. These findings elucidate strategic priorities, innovative solutions, and potential trade-offs that could influence present-day decision-making and long-term planning.

Please see Appendix B, Findings and Research Opportunities for complete descriptions.

Prevalent Key Findings

- Achieving abundant energy in aviation hinges on a confluence of technological advancements and societal acceptance. The adoption of renewable energy, along with infrastructure upgrades, is essential to facilitate sustainable airports, necessitating significant changes to power sources and technologies.
- Societal and environmental changes are as important as technological progress in transforming aviation. These aspects influence the reasons for and nature of travel, dramatically altering the industry's landscape and priorities.
- As an industry reliant on various sectors, aviation contributes about 3% of global carbon emissions, underscoring its role as a smaller player in broader energy transitions, such as the Nation's Hydrogen Hubs initiative.
- Industrial scaling for technologies like hydrogen and SAFs presents substantial challenges. Delays in hydrogen technology certification, coupled with the extensive electricity required for producing aviation fuels, highlight the need for robust infrastructure and regulatory standards.
- While solar energy is promising for distributed power generation, its widespread adoption depends heavily on advancements in energy storage as capacitance between the misaligned timeframes of solar energy generation and grid energy demand Fission and fusion may become crucial in meeting future energy demands, alongside other renewable sources.
- Current limitations in data regarding total water availability and airport energy usage in the US, along with the absence of studies comparable to the European Hydrogen Aviation report, emphasize the need for comprehensive research and model predictions to guide sustainable transitions.

Significant Key Findings

- A large hub airport currently utilizes energy equivalent to a large nuclear power plant when accounting for both operations and fuel consumption.
- A gap persists between industry sustainability goals and actual technology adoption, necessitating a transitional environment where hydrogen and other fuels coexist.
- The future viability of liquid hydrogen in widebody and long-haul flight segments will require substantial aircraft redesign.
- Development of alternate power sources requires careful evaluation of their environmental and societal impacts. In this context, nuclear power, including small modular reactors (SMRs), could significantly bolster airport and aircraft energy systems, although the U.S. lags European advancements. Power distribution advancements must align with a distributed power generation model that includes solar, wind, and maritime energy sources.
- Climate resilience, especially in coastal airports, demands adaptive infrastructure like amphibious architectures.
- AI, alongside advancements in various technologies such as biometrics, extended reality (XR)/virtual technologies and quantum computing, offers transformative potential for airport operations.

- Ground transportation advancements are poised to reshape short-haul flights and airport designs. An integrated transportation network, factoring in emerging space-based travel, can lead to an evolution in airport architectures.

Surprising Key Findings

- The current SAF production challenges project achieves the FAA's 2030 goal without addressing scale and adoption barriers. The term SAFs may inaccurately reflect its composition since it often includes traditional jet fuels. For the next few decades, jet fuel will continue to play a significant role in aviation, particularly for high-speed or long-distance travel.
- Technical solutions exist for critical energy transition barriers, such as electrolysis and storage, but these involve significant energy inefficiency and infrastructure requirements pose significant challenges calling for potential government intervention.
- Models indicate the NPIAS could support energy independence, substantially contributing to the grid and supporting national hydrogen hubs.
- However, looming water scarcity issues, conspicuously absent from aviation's sustainable approach, emphasize the need for integrating water usage considerations into future planning.
- Projections suggest that airports could evolve into biomimetic energy hubs, spurring circular economies and broader societal roles, including temporary housing and resource distribution centers for climate refugees.

Research Opportunities

Research opportunities in future airport energy systems span multiple time horizons and technological readiness levels. These opportunities are categorized into three levels, representing increasing complexity and development timeframes. Low level opportunities as described here focus on near-term implementations of existing technologies and system optimizations (next decade). Mid level opportunities address emerging technologies and systemic transformations (10-30 years). High level opportunities explore revolutionary concepts that could fundamentally reshape aviation infrastructure (30+ years). Each category balances immediate practical needs with long-term technological possibilities, while considering sustainability, efficiency, and resilience requirements.

- Low Level Opportunities (10-30 years):
  - **Distributed Hydrogen Economy Prototype** - Technical partnership model for scaled hydrogen infrastructure and market development. Initial research should focus on developing standardized interfaces and transport protocols for hydrogen hubs that allow cross-industry adoption.
  - **Multi-fuel Airport Infrastructure Transition** - Integration framework for diverse energy sources with AI optimization. Comparative performance studies of various fuel storage and transport systems at airports would identify transition and adoption pathways for existing infrastructure.
  - **Self-Sufficient Airport Ecosystems** - Autonomous resource management and supply chain resilience model. Creating digital twin simulations of resource flows would identify dependencies and opportunities for closed-loop systems.
  - **Circular Economy Implementation** - AI-driven sustainable resource hub transformation. Developing waste stream models would identify recovery opportunities specific to operations and services.
  - **NPIAS Network Electric/Hydrogen Infrastructure** - Comprehensive national infrastructure integration strategy. Mapping energy supply and demand patterns

would reveal optimal placement for initial hydrogen and electric infrastructure investments.
  - **Climate Warming Impact Analysis** - Advanced system adaptation modeling for temperature impacts. Conducting multi-parameter sensitivity analyses and correlating these to varied climate scenarios may identify the most vulnerable systems which require immediate adaptation.
  - **Fast Conversion Charging/Fueling** - Universal standardized energy transfer systems. Investigating high-throughput cryogenic fluid transfer systems would address bottlenecks in hydrogen-powered aircraft turnaround times.
  - **AR/Holographic Airport Architecture** - Scalable virtual facility optimization in order to optimize design before build. Prototyping hybrid physical-virtual passenger processing environments would quantify operational inefficiencies and identify essential infrastructure requirements.
  - **Aeronautical Data Mining Economy** - Secure aviation data marketplace. Developing federated learning frameworks would enable the collection of aeronautics hardware insights (e.g., digital twins) combined with preserving proprietary information and enhancing cybersecurity.
  - **NPIAS Virtual Power Utility Business Case** - Integrated solar implementation study. Airport campus usage analyses would quantify the renewable generation potential across various airport classifications and geographic locations.

- Mid Level Opportunities (10-30 years):
  - **AI-Driven Passenger Flow Optimization** - Privacy-preserving monitoring systems. Creating differentially anonymized sensor aggregation algorithms would enable real-time crowd dynamics modeling without compromising sensitive individual passenger data.
  - **AGI Airport Management** - Comprehensive AI oversight with safety redundancies. Developing sandbox testing environments for increasingly autonomous airport management systems would identify decision points for human-AI teaming.
  - **Advanced Electrolysis** - Grey water hydrogen production optimization. Investigating filtration technologies specifically designed for aviation wastewater would enable hydrogen production viable from a previously useless resource.
  - **Quantum Atmospheric Monitoring** - Entanglement-based traffic management with climate integration. Exploring quantum sensing technologies may provide unprecedented resolutions of atmospheric data useful for optimizing aircraft routing in dynamic conditions.
  - **Quantum Energy Modeling** - Advanced sustainable energy simulation platform. Advancing quantum methods for complex energy system modeling would reveal optimization opportunities unknown to classical computing approaches.
  - **Self-Sufficient Airport Ecosystems** - Integrated resource management systems. Developing adaptive control systems (that balance multiple resource streams) would enhance resilience against supply chain disruptions and extreme weather.
  - **Personal Data Management Platform** - Secure biometric data monetization. Creating cryptographic frameworks for privacy-preserving commerce would allow passengers to both benefit and profit from their personal data.
  - **Distributed Energy Microgrid Market** - Resilient decentralized energy ecosystem. Developing peer-to-peer, micropayment, arbitrage energy trading protocols would enable broadly diverse resource sharing between airports and surrounding communities applicable to both normal and emergency operations.

- High Level Opportunities (30+ years):
  - **Oceanic Gyrostatic/Amphibious Airport** - Dynamic floating aviation platforms. Investigating biomimetic response systems inspired by marine organisms would create platforms that actively counteract ocean dynamics while harvesting wave energy.
  - **Stratospheric Aerostatic Airport** - High-altitude operations with energy harvesting. Investigating atmospheric density gradient energy extraction would create self-sustaining platforms that harness temperature differentials and high-altitude wind shear while serving as stratospheric waypoints.
  - **Self-Repairing Bio-Digital Ecosystem** - Adaptive living infrastructure systems. Developing symbiotic relationships between engineered microorganisms and novel, biotic materials would create infrastructure that continuously evolves to address emerging challenges.
  - **Gravity-Manipulated Operations** - Quantum physics-based logistics automation. Investigating quantum vacuum fluctuation effects would reveal potential methods for localized gravitational field manipulation that transcend current physics limitations.
  - **In-flight Multimodal Coordination** - Seamless transportation integration. Developing predictive passenger-aware and passenger-intention algorithms would create transportation systems that anticipate and fulfill mobility needs before they're explicitly requested.
  - **Small Nuclear Reactor Integration** - Airport energy independence through SMR deployment. Exploring accelerator-driven subcritical reactor designs may provide safe nuclear energy generation with minimal waste.
  - **Advanced Biotic Systems** - Bio-Digital airport management paradigms. Developing genetically engineered structural organisms would create living airports that self-construct, collect energy, adapt to changing conditions, observe planned senescence and safety models and heal damage.
  - **Space-Based Power Systems** - Next-generation energy harvesting networks. Exploring quantum entanglement for energy transfer would eliminate transmission losses between orbital power generation and terrestrial consumption points.
  - **Extra-Planetary Airport Infrastructure** - Adaptable aeronautical facilities for lunar, Martian, and other extraterrestrial operations. Developing orbital manufacturing models for deployable In Situ Resource Utilization (ISRU) biotic deployment methods would enable efficient development of facilities using only native extraterrestrial materials.
  - **Multi-Domain Airport Systems** - Integrated hovering, marine, submarine, and subterranean aviation facilities. Exploring phase-changing metamaterials would create unified structural systems capable of operating seamlessly across multiple environmental domains.

Subject Matter Expert Involvement

This study needed verification of timelines and direction for validation of its findings. One approach was to survey the existing literature by various organizations as to projections related to sustainable aviation. Table 1 surveys publicly available roadmaps from both industry and government related to the adoption of renewable aviation, including the introduction of alternate fuels such as SAFs and hydrogen. The overall pattern of these roadmaps is consistent with those shown. However, as noted elsewhere within the study, implementation of such timelines will require significant investment. For example, the introduction of SAFs lags the publicly available projections and may not be met without significant changes in infrastructure.

The research team engaged with a diverse group of eighteen subject matter experts (SMEs) representing key stakeholders across multiple disciplines relevant to future airport infrastructure. Interviewees included executives from fusion energy companies, utility grid operations, legacy energy corporations, cloud computing providers, airport management, sustainability leadership, and aerospace engineering. This expert input brought perspectives from both public and private sectors, with several participants having extensive international experience in infrastructure design and implementation. Areas of expertise encompassed next-generation energy production, smart infrastructure development, transportation systems architecture, urban planning, advanced manufacturing, and sustainable operations. Emphasis was placed on participants with cross-disciplinary backgrounds who could provide insights on the integration challenges between emerging technologies and existing aviation infrastructure. The interviewees collectively represented over 240 years of professional experience across four continents, providing a global perspective on future aviation needs.

In particular, we conducted interviews with SMEs to develop more accurate, reliable, and actionable forecasts. SMEs were identified within relevant industries of interest to this research and included representation from airports, aeronautics, and energy from both government and commercial sectors. Scripts were developed for use as a guide during interviews to ensure consistency and focus, efficiency, comprehensive coverage, clarity and understanding, and data analysis. While these guides proved to be beneficial, interviews were sufficiently flexible to allow for deeper dives into topics and to encourage the SMEs to provide their unique insights. Generally, the SME interviews validated the desk research we had conducted. However, researchers were unable to interview SMEs in sufficient quantity to preclude biases the research team may have included. Further, hydrogen as an energy source for aviation was given research priority and therefore is reflected prominently in the research teams' conversations with the SMEs.

Table 1: Industry and Government Sustainable Aviation Timelines (5-10)

	2025	**2030**	**2035**	**2040**	**2045**	**2050**
Embraer	first flight H2-powered electric demonstrator	eVTOL and 100% SAF compatibility	Energia Family of Regional Aircraft 100% renewables		H2 powered Turboprop	H2 powered E2 and net zero CO2 emissions
Airbus	aircraft and helicopters can operate on a 50% blend of SAF	aircraft and helicopters capable of operating on a 100% blend of SAF	H2 powered commercial aircraft			Net zero CO2 emissions
Boeing		Urban & Sub Regional - battery & fuel cell, Regional-, Short-, and Long-haul - SAF & H2 for SAF		Urban & Sub Regional – H2 fuel cell, Regional-, Short-, and Long-haul - H2 combustion		Net zero CO2 emissions

FAA Aviation Climate Action Plan		3 billion gal./yr. SAF, 30% fuel efficiency improvement through R&D				Net-Zero GHG Emissions from the U.S. Aviation Sector, Reduce impacts of noise and air quality on airport communities
U.S. Department of Energy Transmission Interconnect Roadmap			Measurable Targets for Interconnection Reform			
U.S. National Clean Hydrogen Strategy and Roadmap	Focus on regional networks, H2 production cost $2/kg	50% ↓ GHG emissions from 2005 levels, 10 MMT clean H2 production, H2 production cost $1/kg	100% carbon pollution free electricity	20 MMT clean H2 production		Net zero GHG emissions, 50 MMT clean H2 production

Discussions primarily focused on the potential of hydrogen as a sustainable fuel source for aviation infrastructure. Participants discussed the technical feasibility, infrastructure challenges, economic viability, and public perception surrounding hydrogen adoption. In our conversations, the SMEs emphasized the need for a multi-fuel approach, including hydrogen and SAFs, due to the challenges of transitioning the entire aviation industry to hydrogen. SMEs identified Airbus's decision to adopt hydrogen technology as a potential catalyst for industry-wide change and highlighted the need for significant investment in airport infrastructure to accommodate hydrogen and electrification. Challenges and considerations of moving the aviation industry to a hydrogen economy include:

- High upfront costs for hydrogen infrastructure
- Public perception and acceptance of hydrogen
- Multi-fuel approach complicating airport operations,
- Uncertainty about the future of SAFs

SMEs provided potential solutions to mitigate these challenges including:

- Modular hydrogen storage and distribution systems
- Education and outreach campaigns
- Collaboration between airlines, airports, and governments
- Continued research and development

Overall, SME interviews highlighted the technical feasibility of hydrogen and emphasized the critical role of infrastructure development, economic factors, and public perception in realizing hydrogen’s full potential.

Conclusion

This study on envisioning zero-carbon, sustainable hub-scale airports fifty years into the future has provided an overview of the technological, economic, and societal transformations that might be needed to achieve these ambitious visions. By employing a multidisciplinary approach that integrates Political, Economic, Social, Technological, Environmental, and Legal

(PESTEL) factors, the study has identified pivotal areas for technology development and potential pathways to overcome the current barriers hindering the transition to sustainable aviation. The future scenarios and backcasting methods used in the research potentially offer insights into the steps required to reach these envisioned futures, emphasizing the importance of starting now to create the necessary foundations.

The research highlights the critical role of hydrogen and SAFs in the future energy landscape of aviation. Hydrogen is projected to play a transformative role in decarbonizing air travel, with advancements in electrolysis technology and infrastructure development being key to its widespread adoption. The study also underscores the potential of SAFs as a transitional fuel, offering immediate reductions in lifecycle CO_2 emissions without the need for significant modifications to existing aircraft and fueling infrastructure. The multi-fuel approach, incorporating both hydrogen and SAFs, is presented as a pragmatic strategy to navigate the complex transition towards zero-carbon aviation.

Future airports are envisioned to become multi-modal transportation hubs, integrating advanced technologies such as fusion energy, AI-driven systems, and quantum computing. These innovations are expected to enhance operational efficiency, security, and passenger experience while promoting environmental sustainability. The scenarios describe a progression where airports evolve into increasingly critical nodes of economic and cultural exchange, supporting various modes of transportation and adapting to future socioeconomic and environmental conditions. The anticipated growth in passenger traffic and energy demands necessitates the development of resilient, adaptable infrastructure capable of accommodating new aircraft and power generation methods.

To build on these insights, several actionable recommendations are proposed: (1) Prioritize investments in hydrogen infrastructure development, including regional hydrogen hubs and scalable modular hydrogen systems. (2) Accelerate adoption across infrastructural developments that coincide with technical depth of analysis. (3) Establish robust regulatory frameworks and financial incentives, promoting education and public outreach, and implementing pilot projects for multimodal and resilient infrastructure. (4) Foster collaboration among stakeholders, in preparation for regulatory and technological changes, and continuous monitoring and adaptation to global temperature change impacts. By exploring ways to implement these recommendations, the aviation industry will be poised to begin to effectively navigate the transition towards sustainable, zero-carbon hub-scale airports responding to global temperature change.

In conclusion, the study provides a forward-looking framework that not only addresses the technical and infrastructural developments required for sustainable aviation but also considers the broader societal, economic, and environmental implications. The identified technology enablers and pivot points serve as critical milestones that can significantly shape the future of aviation. By leveraging the insights from this research, stakeholders in the aviation industry can strategically plan and invest in innovations that pave the way for a sustainable and zero-carbon future, ensuring the continued connectivity and economic vitality of global transportation networks.

Appendix A: Calculations related to NPIAS study

Table 2: Solar Panel Efficiency and Requirements

Solar Constant (in space)	1370	W/m2	
Solar Irradiance (at Earth's surface)	1000	W/m2	

Current best solar technology efficiency	25%		[Champion Photovoltaic Module Efficiency Chart | Photovoltaic Research | NREL]
Current best solar power density	250	W/m2	
Shockley-Queisser Limit (single junction)	32%		[Shockley–Queisser limit - Wikipedia]
Shockley-Queisser Limit (infinite junction)	86%		[Overcoming Shockley–Queisser Limit: Why and How? (researchhub.com)]
Hours of sun in a day	7.50	hrs	
Hours in a year	2737.5		
m2 in a km2	1.00E+06		
percent of land covered by solar panels	75%		
Whr per year per km2	5.13E+11	Wh/year/km2	
land needed for 10 PetaWhr	1.95E+04	km2	roughly 25% of Mojave Desert

Table 3: NPIAS Solar Power Production Constants and Parameters

PV Potential	0.2	MW/acre				
Solar Land Ratio	0.5	land used for solar/total land on airport				
U.S. Commercial Aviation Jet Fuel Requirement, 2030	1.45E+10	gallons		<- 100% of 2030 Jet fuel		14,470,000,000
Jet fuel energy per gallon	1.25E+05	BTU/gallon				
Imperial to Metric	2.93E-04	kwh/BTU				
Jet Fuel Energy	**530**	TWh		AAM requirement		0.05
H2 electrolysis energy	52.50	kwh/kg		Energy consumed in electrolysis/HHV of H2		
LH2 liquifaction energy	10.00	kwh/kg		Energy consumed in liquefaction/HHV of H2		
LH2 energy	33.00	kwh/kg		Lower heating value (energy) of LH2		
LH2 Production Efficiency	53%			LHV of H2/energy required to electrolyze and liquefy it		
Full H2 Aviation Energy Req	**1003.96**	TWh				

Table 4: NPIAS Solar Power Production Capability and Airport Baseload on a Per State Basis

	Airport Land Area [acres]	Land Available for Solar [acres]	Hours of Sunlight Per Year [USGS/NOAA source]	ANNUAL SOLAR GENERATING POTENTIAL [MWh]	Hub Airport Baseload [MWh]	Non-Hub/GA AIRPORT BASELOAD [MWh]

Alaska	65,527	32,764	1,958	12,830,187	5,000	903,694
Alabama	21,507	10,754	2,641	5,679,999	9,737	238,274
Arkansas	28,613	14,307	2,771	7,928,662	3,236	253,532
Arizona	34,853	17,427	3,870	13,488,111	88,974	199,428
California	83,538	41,769	3,050	25,479,090	154,362	599,108
Colorado	33,396	16,698	3,150	10,519,740	35,078	176,500
Connecticut	2,000	1,000	2,585	517,000	3,992	29,774
DC	888	444	2,528	224,486	48,635	3,464
Delaware	1,191	596	2,500	297,750	-	10,392
Florida	95,597	47,799	3,113	29,759,346	284,215	278,440
Georgia	37,558	18,779	2,863	10,752,855	84,133	337,988
Hawaii	2,209	1,105	3,038	671,094	55,046	35,300
Iowa	24,262	12,131	2,550	6,186,810	4,502	265,986
Idaho	12,595	6,298	2,993	3,769,684	4,573	128,086
Illinois	49,834	24,917	2,567	12,792,388	68,674	272,832
Indiana	26,615	13,308	2,400	6,387,600	14,515	203,634
Kansas	38,636	19,318	2,900	11,204,440	4,113	271,512
Kentucky	10,824	5,412	2,500	2,706,000	17,429	184,252
Louisiana	30,449	15,225	2,650	8,068,985	11,757	192,500
Massachusetts	10,629	5,315	2,630	2,795,427	58,061	88,580
Maryland	7,027	3,514	2,520	1,770,804	34,087	63,012
Maine	14,977	7,489	2,513	3,763,720	1,935	123,962
Michigan	48,889	24,445	2,430	11,880,027	36,305	335,102
Minnesota	39,886	19,943	2,726	10,872,924	38,707	340,050

Missouri	21,749	10,875	2,651	5,765,660	39,614	232,748
Mississippi	23,759	11,880	2,720	6,462,448	924	256,914
Montana	28,897	14,449	2,735	7,903,330	3,145	242,398
North Carolina	26,635	13,318	2,775	7,391,213	41,395	228,542
North Dakota	18,727	9,364	2,650	4,962,655	-	192,500
Nebraska	34,410	17,205	2,750	9,462,750	4,452	249,326
New Hampshire	7,588	3,794	2,520	1,912,176	1,914	50,558
New Jersey	9,376	4,688	2,520	2,362,752	47,632	74,806
New Mexico	35,046	17,523	3,400	11,915,640	6,940	160,664
Nevada	29,166	14,583	3,700	10,791,420	27,486	101,116
New York	19,484	9,742	2,603	5,071,685	107,770	222,274
Ohio	31,462	15,731	2,248	7,072,658	18,568	314,482
Oklahoma	39,536	19,768	3,052	12,066,387	5,403	340,132
Oregon	22,637	11,319	2,340	5,297,058	16,475	168,334
Pennsylvania	16,894	8,447	2,300	3,885,620	46,973	190,438
Rhode Island	2,364	1,182	2,615	618,186	4,258	32,496
South Carolina	19,025	9,513	2,813	5,351,733	15,788	166,932
South Dakota	18,762	9,381	2,825	5,300,265	959	205,696
Tennessee	15,247	7,624	2,550	3,887,985	23,194	216,830
Texas	96,323	48,162	2,700	26,007,210	149,267	700,884
Utah	16,208	8,104	3,030	4,911,024	31,174	123,220
Virginia	17,113	8,557	2,763	4,728,322	7,125	155,798
Vermont	1,962	981	2,250	441,450	1,113	34,640
Washington	31,138	15,569	2,175	6,772,515	37,404	235,388
Wisconsin	38,633	19,317	2,454	9,480,538	12,713	303,348

West Virginia	7,657	3,829	2,100	1,607,970	-	77,528
Wyoming	25,538	12,769	3,031	7,740,568	-	132,870
Total	1,376,836	688,418	137,716	379,518,345	1,718,749	10,946,264
				380	TWh	**13**

Table 5: Proportion of Green LH2 Aviation Production Potentially Generated by PV Solar on GA Airport Land in the U.S.

Potential 2030 Energy Demand at All Airports		
Total Estimated LH2 Aviation Fuel Energy Demand (assuming an energy equivalent of the U.S. projected jet fuel 2030 requirement of 14.5B gallons all converted to LH2 at a 53% LH2 production efficiency)	1,004	TWh
Total Projected GA and Hub Airports Baseload Demand	13	TWh
Potential Solar Energy Supply from GA Airport Land		
Total NPIAS Solar Power Production Capability (assuming half of all total GA airport land is used for solar at 0.2 MW/acre)	380	TWh
Proportion of Fully Converted LH2 Fuel and Baseload Airport Energy Demand that GA Airport-Based Solar Energy Could Provide	**37%**	

Appendix B: Technology and Scenario Figures

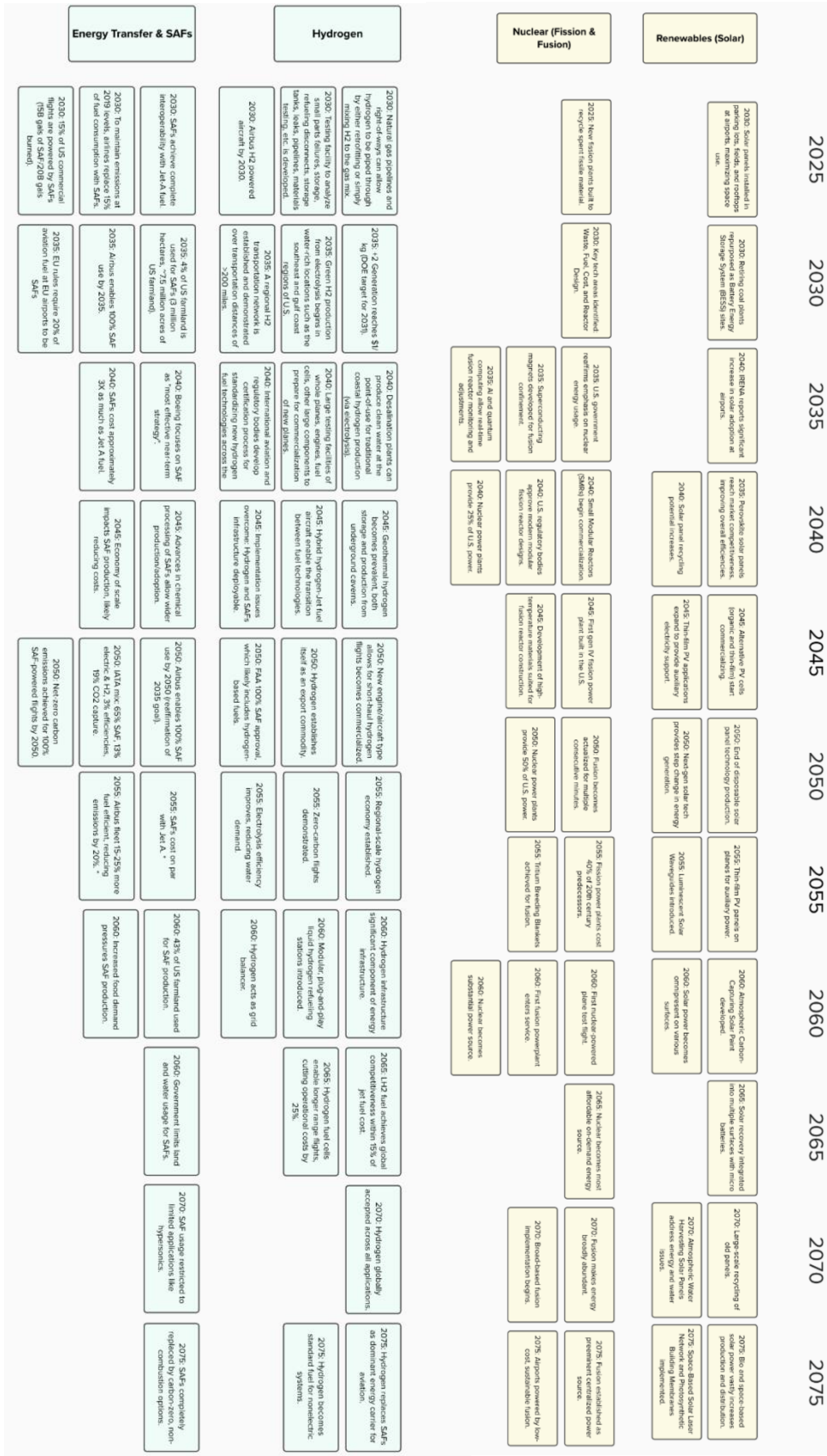

Figure 14: Progression across various Power Swimlanes (fields) and across decade leading towards an Abundant Power Future State in 2075.

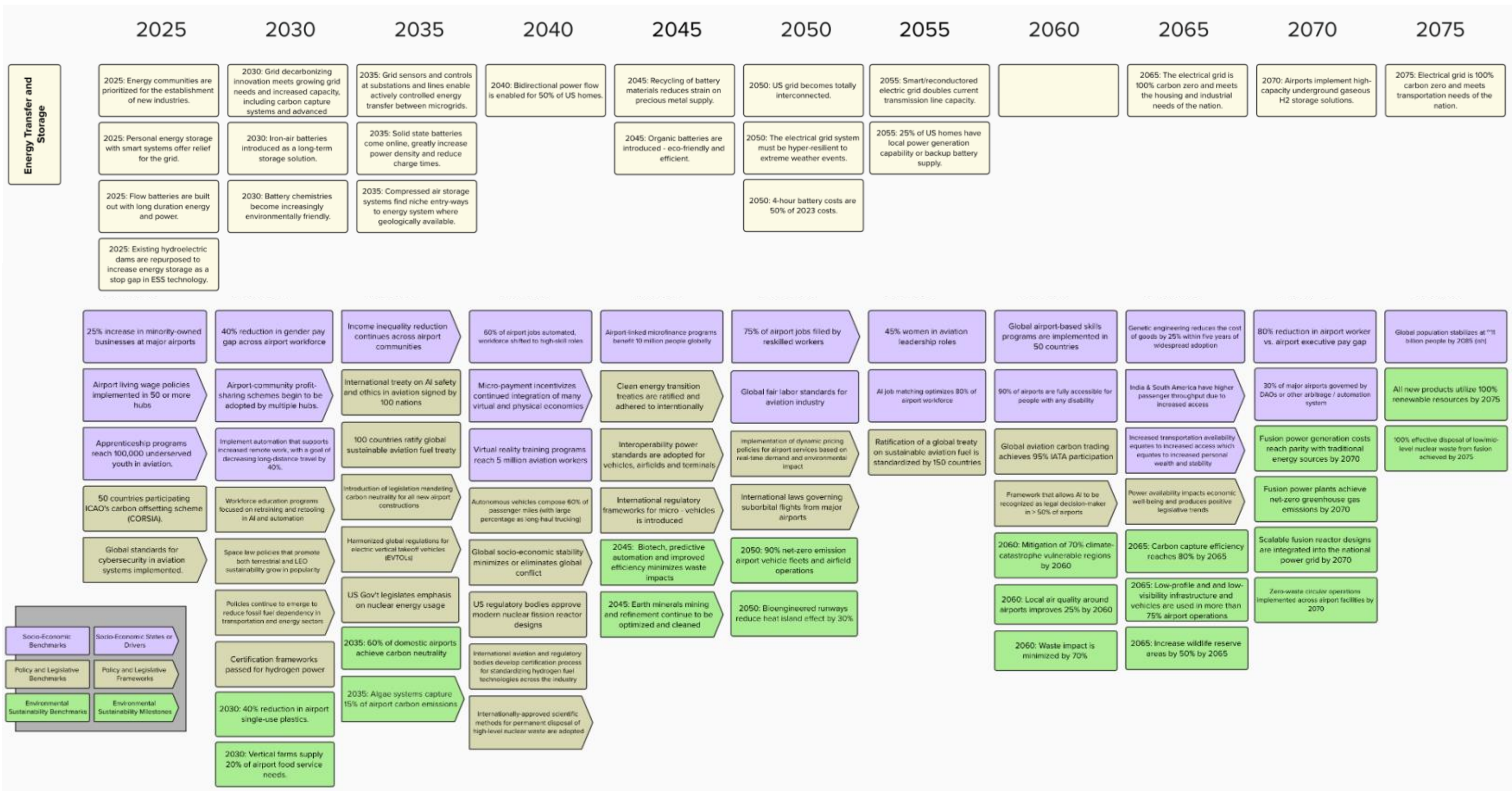

Figure 15. Progression across various PESTL Swimlanes (fields) and across decade leading towards an Abundant Power Future State in 2075

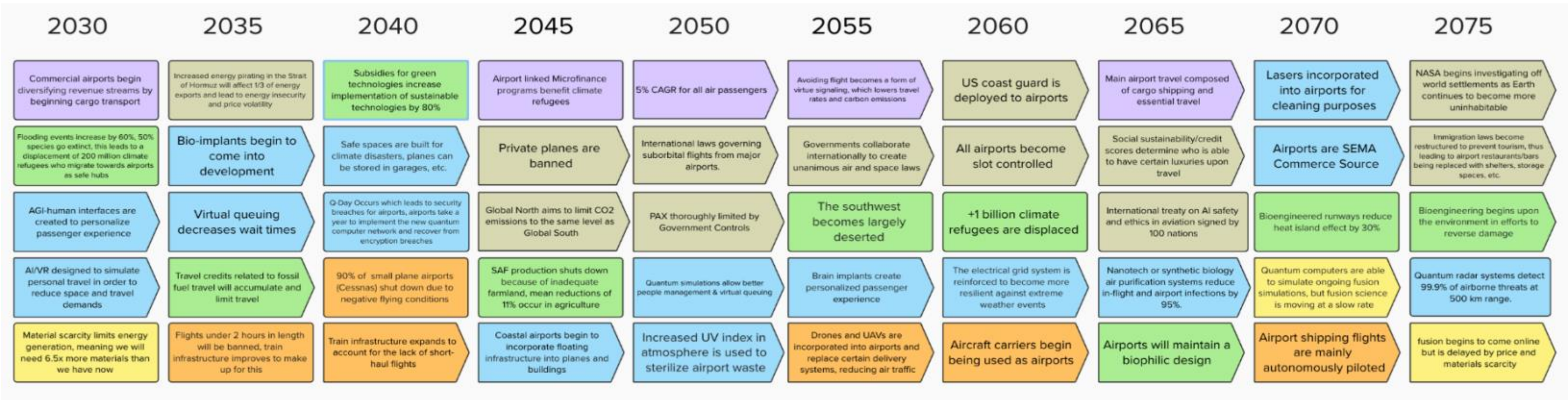

Figure 17: Progression across various Swimlanes and across the decades leading towards a Constrained Discipline Future State in 2075.

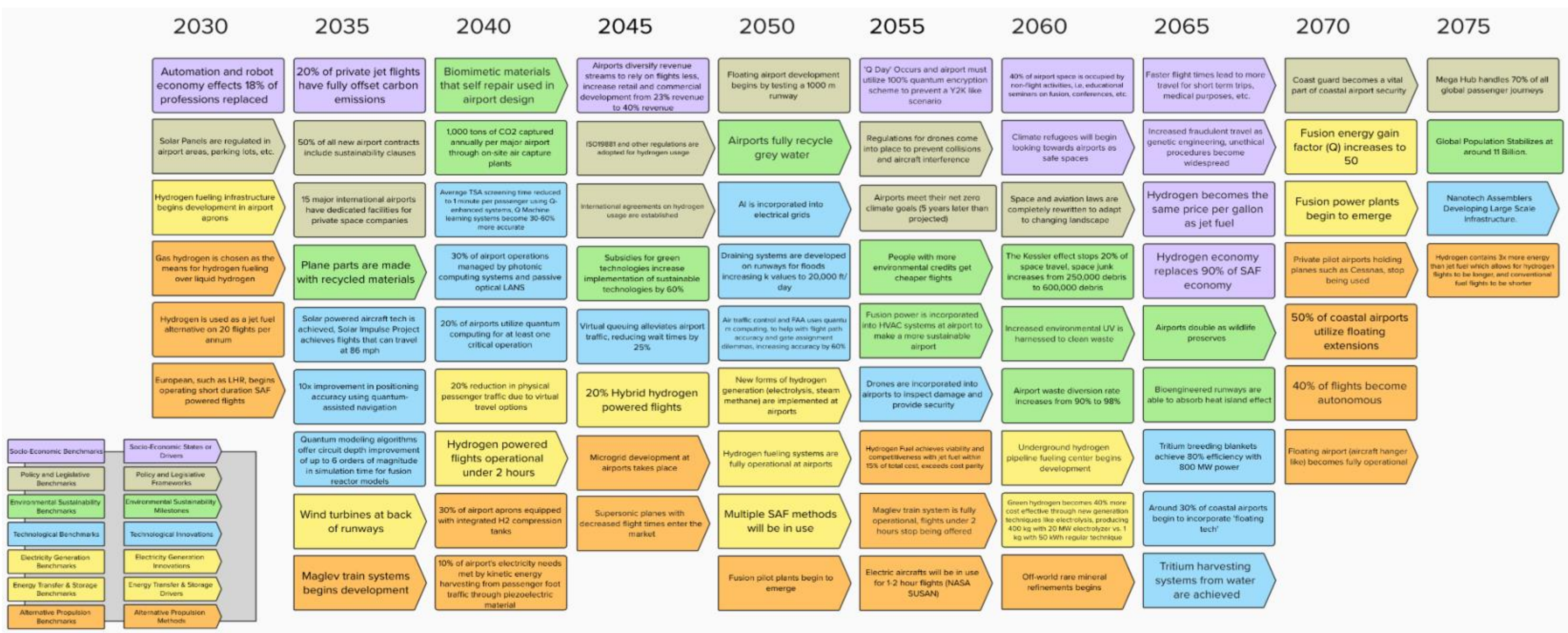

Figure 16: Progression across various Swimlanes and across decades leading towards an Climate Adaption Future State in 2075.

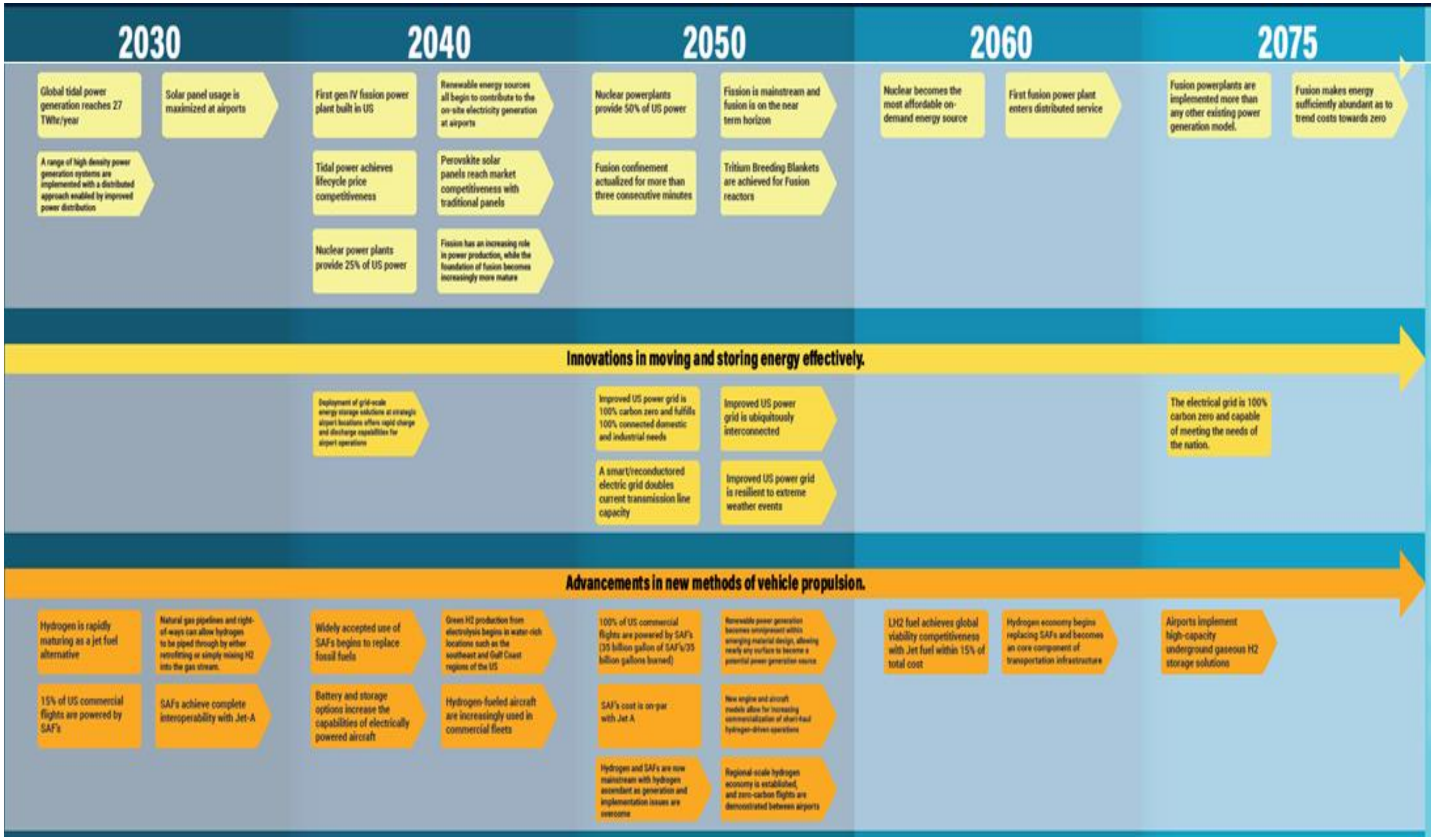

Figure 18: Abundant Energy Technology Timeline

Appendix C: Additional Research Opportunities

Distributed Hydrogen Economy Prototype

- Overview: A distributed hydrogen economy prototype presents a revolutionary approach to energy systems, integrating cutting-edge technologies with economic models. This comprehensive framework leverages AI, advanced software, and secure data systems to orchestrate hydrogen production, storage, and distribution across a network of participants. By simulating real-world scenarios, the prototype offers invaluable insights into optimizing energy flows, pricing strategies, and infrastructure integration, paving the way for a sustainable, hydrogen-powered future.
- Research Questions: How can a hydrogen economy prototype efficiently integrate all participants using smart technologies, AI-driven pricing models, and advanced management systems? What key software platforms, cybersecurity measures, and micropayment technologies are essential for a secure and transparent hydrogen economy? How can digital twins and standardized interfaces optimize operations and ensure interoperability across the hydrogen ecosystem and legacy energy systems?

Multi-fuel Airport and Infrastructure Transition

- Overview: The transition to sustainable aviation energy solutions requires airports to adapt to multiple fuel types simultaneously. This shift integrates hydrogen, SAFs, batteries, and legacy fuels, necessitating evolution in airport layouts, operations, and digital infrastructure. The transition model aims to create flexible, efficient systems capable of managing diverse energy sources while maintaining safety and operational efficiency.
- Research Questions: How can airports efficiently manage multi-fuel refueling systems, optimize layouts, and adapt infrastructure to support the transition to sustainable aviation energy solutions? What AI-driven systems, cybersecurity measures, and blockchain technologies are necessary for optimizing fuel distribution, ensuring safety, and enhancing traceability across various energy types? How can digital twins, simulation software, and standardized protocols aid in repurposing legacy infrastructure and ensuring interoperability between different fuel systems and aircraft types?

Self-Sufficient Airport Ecosystems

- Overview: This concept envisions airports as autonomous, self-sustaining ecosystems, particularly relevant for resource-constrained regions. It integrates comprehensive resource management strategies, including water reuse, on-site energy generation, and food production, to achieve independence from local utilities. This model aims to enhance resilience, reduce environmental impact, and potentially create new economic opportunities within the airport ecosystem.
- Research Questions: How can airports achieve utility independence through integrated resource management, including water reuse, on-site renewable energy generation, and potentially food production? What AI-driven systems and technologies are required to optimize resource allocation and usage across these diverse airport functions, and what are the associated cybersecurity implications? How might this shift towards self-sufficiency impact regional development, air transportation networks, and regulatory frameworks?

Circular Economy Implementation in Airports

- Overview: This concept applies circular economy principles to airport operations, aiming to optimize resource use, minimize waste, and create closed-loop systems. It transforms airports into hubs of sustainable resource management, integrating innovative technologies and processes across various operational areas. The model seeks to enhance environmental performance while potentially improving operational efficiency and creating new value streams within the airport ecosystem.
- Research Questions: How can a comprehensive circular economy model be implemented in airport operations, optimizing key inputs and outputs for circularity, particularly in water usage, energy, materials, and waste management? What technologies, processes, and AI-driven systems are needed to create and optimize closed-loop systems in airports, and how can digital twin technology aid in their simulation and refinement? How might the implementation of circular economy principles impact airport design, operations, financial models, and regulatory frameworks?

Airport Electric/Hydrogen Infrastructure (NPIAS Network) Future

- Overview: This concept envisions a transformed NPIAS, adapted for electrified aviation and Regional Air Mobility (RAM). It proposes a network of airports with integrated electric and hydrogen infrastructure, optimized for new traffic patterns and energy demands. The model aims to create a flexible, efficient, and sustainable aviation ecosystem that accommodates emerging technologies while enhancing overall system capacity and performance.
- Research Questions: How will the availability of electricity and hydrogen at airports influence new route development, traffic patterns, and infrastructure requirements across the NPIAS, private airstrips, and vertiports? What regulatory frameworks, funding mechanisms, and AI-driven modeling techniques are needed to facilitate and optimize this transition, including airspace integration, ground transportation, and community engagement?

Climate Warming Impacts on National Aviation System and Infrastructure

- Overview: This concept addresses the challenges posed by rising global temperatures to the National Plan of Integrated Airport Systems (NPIAS) and the National Airspace System (NAS). It proposes a comprehensive approach to adapt aircraft design, airport infrastructure, and aviation operations for a warmer climate. The model aims to enhance resilience, maintain safety and efficiency, and improve sustainability across the aviation sector in the face of changing environmental conditions.
- Research Questions: How will higher temperatures affect energy consumption, operational efficiency, and safety across the NAS, including impacts on aircraft design, airport infrastructure, and established flight routes? What adaptations in runway design, maintenance practices, and operational capacities are necessary to cope with extreme heat and changing weather patterns? How can AI, predictive analytics, and technological innovations be used to optimize flight operations, infrastructure management, and worker safety, mitigating aviation's environmental footprint?

Fast Conversion Charging, and Fueling

- Overview: This method of power transfer addresses the challenge of integrating novel energy storage technologies into commercial aviation while maintaining efficient refueling times. It proposes a flexible energy ecosystem capable of rapidly converting between various energy forms, including liquid and gaseous hydrogen. The model aims to standardize high-flow-rate transfer systems and develop efficient energy conversion devices, ensuring compatibility with existing infrastructure and meeting the industry's 20-minute refueling benchmark.

- Research Questions: How can high flow rate liquid and gaseous hydrogen transfer systems and connectors be improved and standardized? What are the most promising designs for efficient energy conversion devices that can rapidly transform renewable energy into forms suitable for various airport applications? How can these fast conversion and fueling technologies be integrated into existing airport infrastructure to create a highly adaptable and robust energy ecosystem that meets the 20-minute refueling time constraint?

AR / Holographic Airport Architectures

- Overview: This new model of architecture leverages augmented reality and holographic technology to expand airport capabilities without physical construction. It proposes a hybrid environment where virtual and physical spaces seamlessly integrate, enabling the creation of scalable, flexible airport facilities. The model aims to enhance infrastructure utilization, improve accessibility for remote users, and create new revenue streams while minimizing environmental impact and construction costs.
- Research Questions: How can augmented reality and holographic technology be implemented to create scalable virtual airport environments that seamlessly integrate with physical spaces? What are the technical requirements and best practices for overlaying virtual infrastructure onto physical spaces and vice versa, including fiducials, AR targets, and real-time volumetric mapping? How can virtual shops, lounges, and services be integrated to reduce physical infrastructure needs while maintaining a seamless, profitable, positive experience for both physical and remote passengers?

Aeronautical Data Correlations and Mining Economy

- Overview: This data marketplace proposes a secure marketplace for real-time aeronautical data, unlocking the potential of emergent correlations in aviation. Separate from (but affiliated with) user data this data method aims to create an ecosystem where aircraft performance metrics, atmospheric data, passenger flow patterns, and environmental impact indicators are anonymized, shared, and monetized for platform for airlines, researchers, and tech companies. The model seeks to drive innovation in design, efficiency, operations, and management. User data is dealt with as '**Personal Data Correlations and Management Platform (#IA3)'.**
- Research Questions: How can a secure marketplace for real-time aeronautical data be established, prioritizing key data streams such as aircraft performance metrics, atmospheric data, cargo flow patterns, and environmental impact indicators? How can this marketplace be designed to drive innovations in aviation, maximizing the potential for improvements in aircraft design, operational efficiency, and environmental performance?

AI-Driven Passenger Flow Optimization in Airports

- Overview: This AI-driven system for optimizing passenger flow in airports relies on non-invasive sensors collecting biometric, psychometric, and spatio-temporal data to create a comprehensive, real-time understanding of passenger movement. The model aims to enhance operational efficiency and passenger experience through predictive congestion management and personalized guidance, while addressing privacy and ethical concerns.

- Research Questions: What non-invasive sensor technologies and AI algorithms are most effective for collecting and analyzing multi-dimensional passenger data to optimize real-time flow and predict congestion in airports? How can privacy concerns, ethical considerations, and cybersecurity measures be addressed in the implementation of these AI-driven systems? How might digital twin technology and regulatory changes facilitate the development and refinement of comprehensive passenger monitoring and flow management systems?

Artificial General Intelligence (AGI) for Comprehensive Airport Management

- Overview: This Artificial General Intelligence (AGI) system manages the complex, interdependent operations of modern airports. Overseeing a team of specialized AI agents, the AGI integrates and optimizes all aspects of airport management, from air traffic control to maintenance. It enhances operational efficiency, safety, and adaptability while addressing ethical considerations and maintaining effective human oversight.
- Research Questions: What key capabilities and algorithms are required for an AGI system to effectively manage all aspects of airport operations, including real-time data integration and decision-making processes? How can safety protocols, ethical considerations, and cybersecurity measures be integrated into the AGI's design to ensure responsible and secure implementation in critical airport management roles? How might a hierarchical system of AGI and specialized AI agents be designed and tested using digital twin technology to optimize diverse airport functions while maintaining cohesive operations and effective human oversight?

Advanced Electrolysis for Hydrogen Production from Non-Potable Water Sources

- Overview: This advanced electrolysis system efficiently produces hydrogen from non-potable water sources, including grey water. It addresses water scarcity challenges in hydrogen production by utilizing previously unsuitable water inputs. The technology enhances the sustainability of hydrogen production for aviation and other applications, optimizing contaminant removal and energy efficiency in the electrolysis process.
- Research Questions: How can electrolysis technologies be advanced to efficiently process non-potable water sources, addressing technical challenges like contaminant removal and energy efficiency optimization? What are the potential applications, economic implications, and environmental trade-offs of using non-potable water for hydrogen production in water-scarce regions and space applications? How can AI and machine learning be employed to optimize the electrolysis process for varying water inputs, and what regulatory changes might be necessary to implement widespread use of this technology?

Quantum Entangled Air Traffic Control

- Overview: Traditional air traffic management systems struggle with coordination and real-time decision-making, especially with increased air traffic. Voice communication used by air traffic control can lead to miscommunication, and these systems are vulnerable to hacking.
- Research Questions: How can quantum entanglement be harnessed to create an instantaneous, secure communication system for global air traffic control, and what are the technical specifications required for such quantum entangled networks to handle real-time air traffic data? How can quantum encryption algorithms be developed and integrated to protect these communications from cyber threats, and what are the challenges and solutions for implementing these quantum systems within existing air traffic control

infrastructure? How can NASA's existing technology, such as the Space Communications and Navigation (SCcaN) program, be leveraged to advance space quantum communication research for aviation applications and prepare for future possible developments like the Quantum Apocalypse ('Q-Day')?

Quantum Modeling for New Forms of Sustainable Energy

- Overview: This quantum computing system models subatomic interactions with high precision to accelerate the development of sustainable energy technologies, particularly hydrogen fuel cells and fusion. It utilizes quantum algorithms and entanglement to simulate complex quantum systems, enabling more accurate predictions and optimizations of energy processes. The system integrates with advanced sensors to identify, track, and predict behaviors at the quantum level, driving innovations in energy efficiency and sustainability.
- Research Questions: How can quantum computers and algorithms be optimized to accurately model and simulate subatomic interactions in hydrogen fuel cells and fusion energy systems? How can quantum entanglement and parallel processing capabilities be leveraged to enhance the efficiency and accuracy of these models, and what are the challenges in scaling quantum simulations for practical energy applications? How can the insights gained from quantum modeling be effectively translated into advancements in sustainable energy technologies?

Self-Repairing Bio-Digital Airport Ecosystem

- Overview: This bio-digital airport ecosystem integrates bioengineering, nanotechnology, and AI to create a living, adaptive infrastructure. The system self-repairs, reconfigures spaces, and grows based on real-time needs and conditions. Utilizing programmable matter and biomimetic principles, the airport learns and evolves like a living organism, optimizing resource utilization and seamlessly adapting to changing technologies and passenger requirements. This biotic, breathing system enhances environmental connectivity and operational efficiency while reducing maintenance costs.
- Research Questions: How can bioengineering, biomimetic practices, and nanotechnology be combined to create a self-managing, self-repairing, modular airport ecosystem that can adapt and evolve like a living organism? What are the technical specifications and materials science advancements needed for programmable matter that can reconfigure itself based on real-time data and changing needs? How can AI be integrated to control and optimize this evolving infrastructure, ensuring adaptability, resilience, and efficient resource utilization while maintaining safety and operational continuity?

Personal Data Correlations and Management Platform

- Overview: This platform empowers passengers to manage and monetize their biometric, behavioral, and personal data within the airport ecosystem. It integrates core methods to ensure data security while creating a marketplace for anonymized personal information. The system enables individuals to control their data, participate in new economic opportunities, and benefit from personalized services. It balances privacy rights with the data needs of AI-driven airport operations, fostering a symbiotic relationship between passengers and advanced airport systems.
- Research Questions: How can an open, secure platform be developed for passengers to manage and monetize their biometric data, incorporating robust encryption and authentication methods? What are the technical specifications and ethical considerations

for creating a marketplace for anonymized data, enabling passengers to securely sell or lease their data? How can this platform balance privacy rights, economic opportunities, and the data needs of AI systems in airport operations? Note, Avionics Data is dealt with in Aeronautical Data Correlations and Mining Economy

Distributed Energy Microgrid Market

- Overview: This distributed energy microgrid system transforms airports into interconnected nodes within a virtual energy network, leveraging the National Plan of Integrated Airport Systems (NPIAS) infrastructure. It creates a decentralized, sustainable energy ecosystem for aviation, optimizing energy generation, storage, and distribution across the network. The system incorporates AI-driven pricing and storage mechanisms to manage peak loads efficiently, enhance energy resilience, and facilitate aviation decarbonization through electricity and hydrogen integration.
- Research Questions: How can a distributed energy microgrid be created to enable connected entities to collect, sell, and optimize energy distribution across the NPIAS network, incorporating AI-driven pricing and storage systems? What regulatory changes and cybersecurity measures are needed to implement an autonomous virtual energy airport authority ($AVEA^2$) while ensuring system protection? How can advanced modeling techniques be used to simulate, refine, and assess the economic and environmental impacts of this virtual energy network on airports and local communities?

Oceanic Gyrostatic / Amphibious Airport

- Overview: This oceanic airport system provides a floating, stable platform for aviation operations in coastal areas. It utilizes advanced stabilization technology and prop designs to counteract wave motion, creating, in one instantiation example, a secure structure on the ocean's surface. The airport harnesses multiple oceanic energy sources, including wave, tidal, solar, wind, OTEC, piezoelectric, and atmospheric electricity, to power its operations and support nearby communities.
- Research Questions: How can gyrostatic stabilization and advanced prop designs be engineered to create a stable, disc-shaped floating airport platform that counteracts wave motion? What are the most effective methods for integrating and optimizing multiple oceanic energy sources (wave, tidal, solar, wind, OTEC, piezoelectric, and atmospheric electricity) to power the airport and nearby communities? How can the environmental impacts of such a structure be assessed and mitigated, considering both marine ecosystem effects and the potential benefits of clean energy generation?

Stratospheric Aerostatic Airport

- Overview: This stratospheric airport system provides a floating aviation platform suspended at 20 km altitude using ultra-lightweight aerogel structures and advanced carbon nanotube tethers. It harnesses abundant stratospheric energy sources through integrated high-efficiency photovoltaic cells, thermoelectric devices, and wind turbines. This design addresses land use conflicts, mitigates vulnerability to sea-level rise and extreme weather, maximizes energy harvesting potential, and reduces atmospheric pollution from conventional aircraft.
- Research Questions: How can ultra-lightweight materials and advanced tethering technologies be engineered to create a stable, buoyant airport platform? What are the most effective methods for integrating high-efficiency photovoltaic cells, thermoelectric devices, and wind turbines to harness stratospheric energy sources? How can aircraft be designed to harvest atmospheric energy during flight, and what technologies are needed

to integrate static electricity, thermal differentials, solar energy, and cosmic radiation into aircraft power systems to achieve net-zero energy flights?

Self-Repairing Bio-Digital Airport Ecosystem

- Overview: This bio-digital airport ecosystem integrates living organisms, nanotechnology, and AI to create a responsive, adaptive infrastructure. The system self-repairs, reconfigures spaces, and grows autonomously, based on real-time needs and environmental conditions. Utilizing programmable matter and biomimetic principles, the airport learns and evolves, optimizing resource utilization and seamlessly adapting to changing technologies and passenger requirements.
- Research Questions: How can bioengineering, biomimetic practices, and nanotechnology be combined to create a self-managing, self-repairing, modular airport ecosystem that can adapt and evolve like a living organism? What are the technical specifications and materials science advancements needed for programmable matter that can reconfigure itself? How can AI be integrated, ensuring adaptability, resilience, and safe biotic resource utilization?

Gravity-Manipulated Operations

- Overview: This gravity manipulation system revolutionizes airport operations by transcending physics limitations in baggage handling, cargo management, and passenger transport. It employs localized gravity control for three-dimensional, energy-efficient movement throughout the airport. The technology uses quantum physics principles like the Casimir Effect and Bose-Einstein Condensates for precise manipulation. This system eliminates conveyor belts and mechanical handling, reducing energy consumption, minimizing lost luggage, and enabling flexible, multi-dimensional airport design.
- Research Questions: How can gravity manipulation technology be engineered for baggage, vehicle, passenger movement, and aircraft guidance? What quantum physics advancements can be applied to develop this technology? How might gravity manipulation revolutionize airport design, operations, and aeronautics, and what new economies and technologies could emerge from this paradigm shift?

Glossary

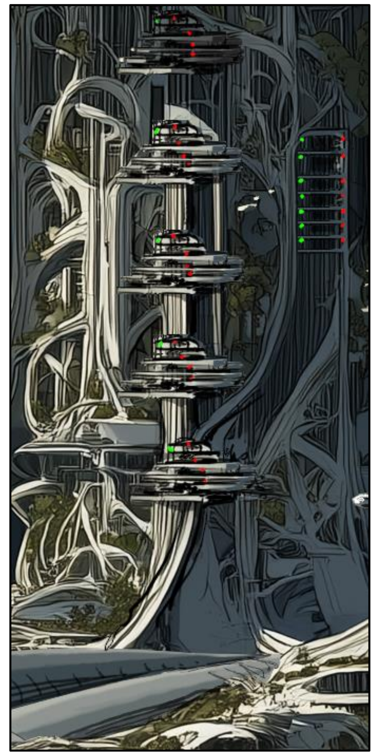

Figure xix: Vertical docking stations for UAM vehicles (Scenario #1)

Advanced Additive Manufacturing - On-demand creation of infrastructure components using programmable metamaterials that enable self-healing and reconfigurable structures.

Aerostatic Airport - A floating aviation platform suspended at high altitude (approximately 20 km) using ultra-lightweight aerogel structures and advanced tethering systems.

AGI (Artificial General Intelligence) - AI systems that match or exceed human reasoning across all intellectual domains, capable of autonomous scientific advancement and complex decision-making.

Ambient Temperature & Pressure Superconducting Materials - Revolutionary materials that conduct electricity with zero resistance at room temperature, eliminating the need for extreme cooling systems.

Ammonia (NH_3) - Alternative aviation fuel with higher volumetric energy density (12.7 MJ/L) than hydrogen, but with toxicity and production challenges.

Amphibious Airport - Airport infrastructure designed to operate both on land and water, adapting to rising sea levels and coastal flooding.

AR (Augmented Reality) - Technology that overlays digital information onto the physical world, proposed for airport navigation and passenger services.

Artificial Ecosystems - Engineered biological systems designed to support biodiversity conservation and environmental restoration within airport facilities.

Backcasting - A planning methodology that starts by defining a desirable future state and works backward to identify the necessary steps and developments required to achieve that future.

Battery-Electric Systems - Energy storage and propulsion systems using electrochemical batteries, limited by energy density for long-haul aviation applications.

Bifacial Solar Panels - Photovoltaic panels that capture sunlight from both sides, increasing energy generation efficiency.

Bio-Digital Airport Ecosystem - Living infrastructure that integrates bioengineering, nanotechnology, and AI to create self-repairing, adaptive airport systems.

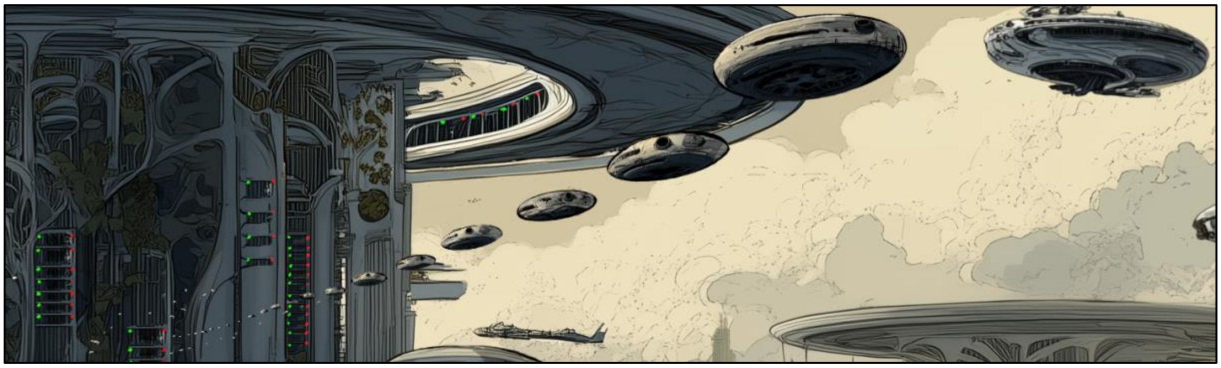

Figure xx: UAM pods approaching the airport in automated formation (Scenario #1)

Biogenic Feedstocks - Organic materials derived from living organisms used in the production of sustainable aviation fuels.

Biomimetic Materials - Engineered materials that mimic biological structures and processes, capable of self-repair, adaptation, and evolution in response to environmental conditions.

Biophotovoltaics - Solar energy systems that use biological processes, such as photosynthesis, to generate electricity.

Bose-Einstein Condensates - Exotic states of matter at extremely low temperatures, potentially useful for quantum computing and gravity manipulation technologies.

CAAFI (Commercial Aviation Alternative Fuel Initiative) - Industry partnership promoting the development and deployment of sustainable aviation fuels.

CAGR (Compound Annual Growth Rate) - The rate of return that would be required for an investment to grow from its beginning balance to its ending balance, used in the study to project passenger growth limitations.

Carbon Credit Systems - Market mechanisms that assign monetary value to carbon dioxide emission reductions, reaching projected values of 600,000 credits/ton in future scenarios.

Casimir Effect - Quantum mechanical phenomenon involving attractive forces between closely spaced surfaces, potentially exploitable for gravity manipulation.

Circular Economy - An economic model that optimizes resource use by minimizing waste and creating closed-loop systems where all byproducts become valuable inputs for other processes.

Climate Adaptation Scenario - One of three future scenarios envisioned for 2075, where airports adapt to significant environmental changes (+2°C global temperature rise) through floating infrastructure and resilient design.

CO_2 (Carbon Dioxide) - Greenhouse gas targeted for capture and utilization in sustainable fuel production and climate change mitigation efforts.

Concentrated Solar Power (CSP) - Solar thermal technology that uses mirrors to concentrate sunlight for high-temperature energy generation.

Constrained Discipline Scenario - The most restrictive of three future scenarios, depicting airports operating under severe resource limitations (+4°C global temperature rise) with necessity-based travel systems.

CSP (Concentrated Solar Power) - Solar energy technology using mirrors and lenses to concentrate sunlight for thermal energy generation.

Cyber-Physical Systems - Integrated networks of physical processes controlled by computer algorithms, essential for smart airport operations.

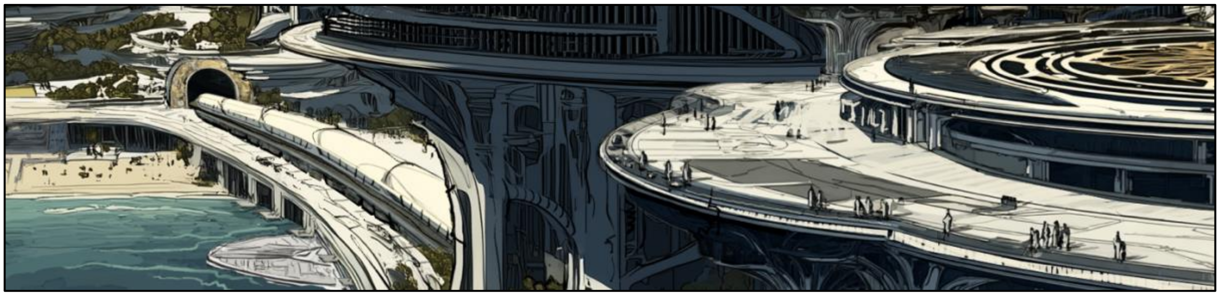

Figure xxi: Maglev trains and forward observation decks over maritime power collection (Scenario #1).

Digital Twins - Real-time digital replicas of physical systems that enable simulation, monitoring, and optimization of airport operations.

Distributed Energy Microgrid - Localized energy networks that can operate independently or in conjunction with the main electrical grid.

Distributed Hydrogen Economy - A decentralized energy system where hydrogen production, storage, and distribution occur across multiple interconnected nodes rather than centralized facilities.

DoE (Department of Energy) - U.S. federal agency responsible for energy policy, including regional hydrogen hubs and renewable energy initiatives.

Drop-in Fuels - Alternative fuels that can be used in existing engines and infrastructure without modifications, such as certain sustainable aviation fuels.

Electrolysis - Process of using electricity to split water (H_2O) into hydrogen and oxygen, fundamental to green hydrogen production.

e-SAF (Electro-Sustainable Aviation Fuel) - Synthetic aviation fuel produced by combining green hydrogen with captured CO_2 using renewable electricity.

Extended Reality (XR) - An umbrella term encompassing virtual reality (VR), augmented reality (AR), and mixed reality (MR) technologies that create immersive digital experiences.

FCH 2JU (Fuel Cells and Hydrogen 2 Joint Undertaking) - European initiative promoting fuel cell and hydrogen technologies.

Fusion Energy - Nuclear fusion power generation that releases energy by combining light atomic nuclei, promising four times the electrical output of conventional fission plants.

Game-Theoretic Analysis - Mathematical modeling approach used to analyze strategic

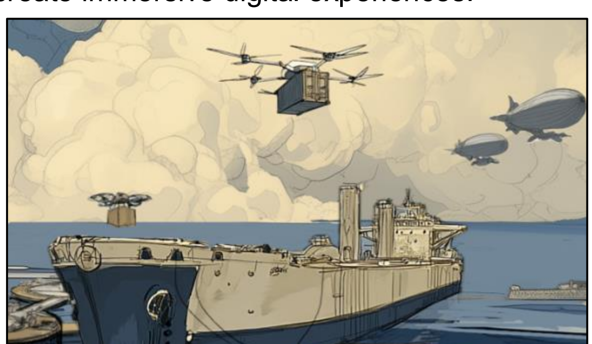

Figure xxii: Maritime, air, and land cargo supply chain support (p 1, Scenario #2).

decision-making between multiple parties, such as airlines and airports adopting hydrogen infrastructure.

Gaseous Hydrogen (GH_2) - Hydrogen stored in gaseous form at high pressure, offering different storage and handling characteristics compared to liquid hydrogen.

GEM Unification Theory - Theoretical framework proposing controlled manipulation of spacetime through unified electromagnetic-gravitational field interactions.

Glassmorphism - Modern design aesthetic using translucent and glass-like visual elements in user interfaces.

Green Hydrogen - Hydrogen produced through electrolysis using renewable energy sources, resulting in zero carbon emissions during production.

GWe (Gigawatts Electric) - Unit of electrical power measurement, with global nuclear capacity approximately 390 GWe as of 2023.

Heat Island Effect - Urban warming phenomenon where developed areas experience higher temperatures than surrounding areas.

Figure xxiii: Maritime, air, and land cargo supply chain support (p 2, Scenario #2).

HHV (Higher Heating Value) - The total amount of heat released when a fuel is completely burned and water vapor is condensed.

Holographic Displays - Three-dimensional visual technology creating floating images without physical screens.

Hybrid-Electric Propulsion - Aircraft propulsion systems combining conventional engines with electric motors and battery systems.

Hydrogen Fuel Cells - Electrochemical devices that convert hydrogen and oxygen into electricity, water, and heat.

Hypersonic Travel - Transportation at speeds exceeding Mach 5 (five times the speed of sound).

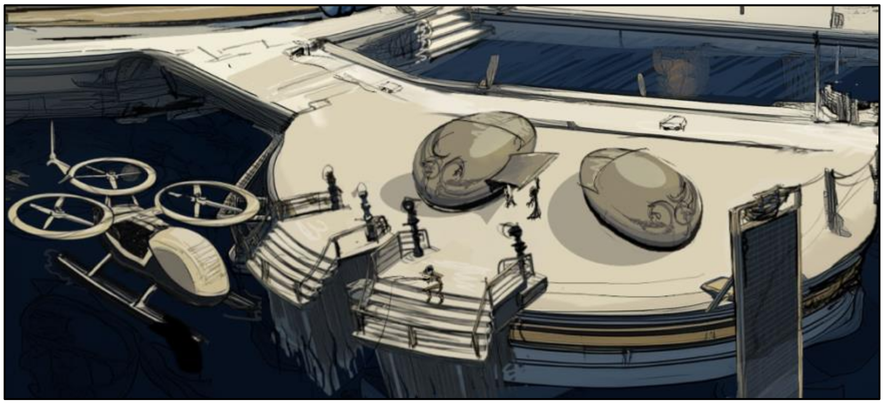

Figure xxiv: Docked maritime-adapted drones docked near coada pods with local fishing for fun (Scenario #2).

ISRU (In Situ Resource Utilization) -

Technology for using local materials and resources, particularly relevant for extraterrestrial applications.

Jet-A - Standard kerosene-based aviation turbine fuel currently used in commercial aircraft.

Kessler Effect - A cascade scenario where space debris collisions generate more debris, potentially making certain orbital regions unusable and affecting space-based operations.

LH_2 (Liquid Hydrogen) - Hydrogen cooled to -253°C for storage and transport, offering high energy density but requiring specialized cryogenic handling systems.

LHV (Lower Heating Value) - The amount of heat released by combustion when water remains in vapor form.

LOE (Low-Emissivity Glass) - Advanced glass technology for improved solar energy collection efficiency.

Maglev (Magnetic Levitation) - Transportation technology using magnetic fields to levitate and propel vehicles without physical contact.

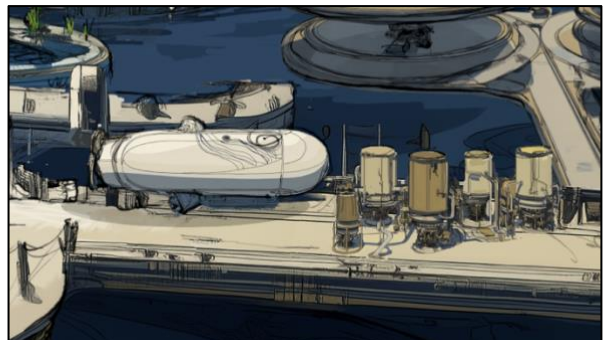

Figure xxv: On-dock liquefaction and and local fusion station (Scenario #2).

Magnetocaloric Energy Recovery - Technology that harvests energy from magnetic field changes and temperature variations.

Maritime Energy - Ocean-based renewable energy sources including wave, tidal, and offshore wind power.

Metamaterials - Artificially structured materials with properties not found in nature, enabling novel electromagnetic and mechanical behaviors.

Multi-Fuel Economy - An energy ecosystem utilizing multiple fuel types simultaneously, including hydrogen, SAFs, battery-electric systems, and conventional fuels.

Nanobots - Microscopic robots capable of performing tasks at the molecular level, potentially useful for maintenance and medical applications.

Nanoscale 3D Printing - Additive manufacturing at the molecular level for creating extremely precise structures and devices.

Nash Equilibrium (NE) - A game theory concept representing a stable state where no participant can improve their outcome by unilaterally changing their strategy.

Neat SAF - 100% sustainable aviation fuel without blending with conventional jet fuel.

Net Zero Emissions - Achieving balance between greenhouse gas emissions produced and removed from the atmosphere.

NPIAS (National Plan of Integrated Airport Systems) - The comprehensive framework of U.S. airports totaling 682,972 acres, analyzed in this study for solar energy generation potential.

NTRS (NASA Technical Reports Server) - NASA's repository for scientific and technical publications.

Nuclear Fission - Nuclear reaction that splits heavy atomic nuclei, currently providing about 10% of global electricity.

Figure xxvi: Maglev city train for transportation and support of aeronautical and maritime supply chain distribution (Scenario #2).

Nuclear Fusion - Nuclear reaction combining light atomic nuclei to release energy, promising abundant clean power.

OTEC (Ocean Thermal Energy Conversion) - Technology that generates electricity from temperature differences between surface and deep ocean water.

Perovskite Solar Cells - Emerging photovoltaic technology using perovskite-structured compounds for potentially higher efficiency and lower costs.

PESTEL Analysis - A framework examining Political, Economic, Social, Technological, Environmental, and Legal factors that influence future scenarios.

Figure xxvii: Convertible protection from extreme weather events and catastrophic storms (Scenario #2).

Photonic Computing - Computing systems that use photons (light particles) instead of electrons for data processing, offering potentially faster and more energy-efficient operations.

Piezoelectric Energy Recovery - Technology that generates electricity from mechanical stress and vibrations.

Pivot Points - Critical junctures in technological evolution that significantly shape future developments and enable multiple potential pathways.

Power-to-Liquid (PtL) - Process converting electrical energy into liquid fuels through chemical synthesis.

Programmable Matter - Materials that can change their physical properties in response to user input or environmental conditions.

PWh (Petawatt Hours) - Unit of energy equal to one quadrillion watt-hours, used to measure global energy consumption and production.

Quantum Computing - Computing technology that leverages quantum mechanical phenomena to process information in ways that could solve complex problems beyond classical computer capabilities.

Quantum Dot Photovoltaics - Solar cell technology using semiconductor nanocrystals for potentially improved efficiency.

Quantum Entanglement - Quantum mechanical phenomenon where particles remain connected regardless of distance, proposed for, among other applications, secure communications.

Regional Air Mobility (RAM) - Short-distance aviation services connecting smaller communities and regional airports, often using emerging aircraft technologies.

Revenue Passenger Kilometers (RPK) - Airline industry metric measuring passenger traffic by multiplying passengers carried by distance traveled.

SAFs (Sustainable Aviation Fuels) - Drop-in replacement fuels derived from renewable feedstocks that can reduce lifecycle greenhouse gas emissions by 60-75% compared to conventional jet fuel.

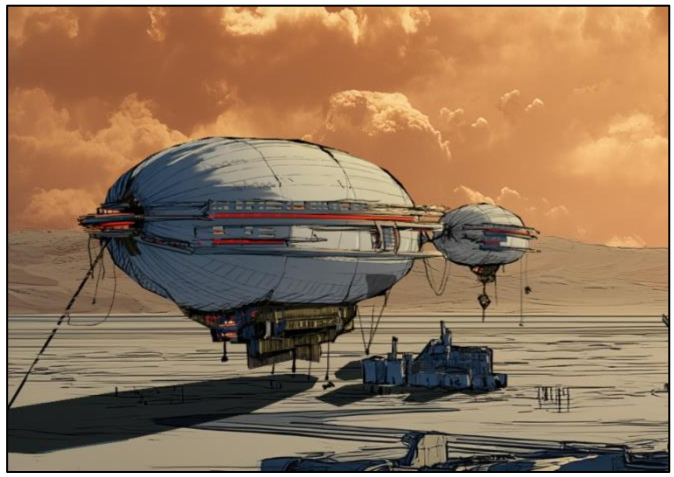

Figure xxviii: Lighter-than-air vehicles for regional transportation, shipping and support under high ambient temperatures (Scenario #3).

SEMA (Sustainable Environmental Management Accreditation) - Environmental certification system for airport operations.

Shockley-Queisser Limit - Theoretical maximum efficiency of single-junction solar cells (approximately 32%).

Smart Dust - Networks of tiny sensors capable of monitoring environmental conditions and structural integrity.

SMRs (Small Modular Reactors) - Compact nuclear fission reactors designed for distributed power generation with enhanced safety features and lower capital costs.

Solar Thermochemical Jet Fuel - Aviation fuel produced using solar energy to drive chemical reactions for fuel synthesis.

Figure xxix: Multi-wing and ornithopter drones for operation under high ambient temperatures and low humidity (Scenario #3).

STI (Scientific and Technical Information) - NASA's comprehensive database of aerospace and related research information.

Subject Matter Experts (SMEs) - Professionals with specialized knowledge in relevant fields who provided expert input and validation for the study's findings and projections.

Superconducting Materials - Materials that conduct electricity with zero resistance, potentially revolutionizing energy transmission and storage systems.

Swim Lanes - Visual organization method used in the study to track the evolution of different technological and societal domains across decades.

Synthetic Biology - Engineering of biological systems for useful purposes, potentially applicable to airport infrastructure and other manufacturing needs.

Figure xxx: Security wall, limited building resources and solar arrays (Scenario #3).

Thermal Loading - The cumulative heat production from widespread deployment of high-density power sources, potentially affecting local and regional thermal gradients.

Thermodynamic Cycles - Processes that convert thermal energy into mechanical work, relevant for various power generation systems.

Third-Generation Feedstocks - Advanced biological materials for sustainable fuel production that don't compete with food crops.

Tritium - Radioactive isotope of hydrogen used in fusion reactions and potentially recoverable from various sources.

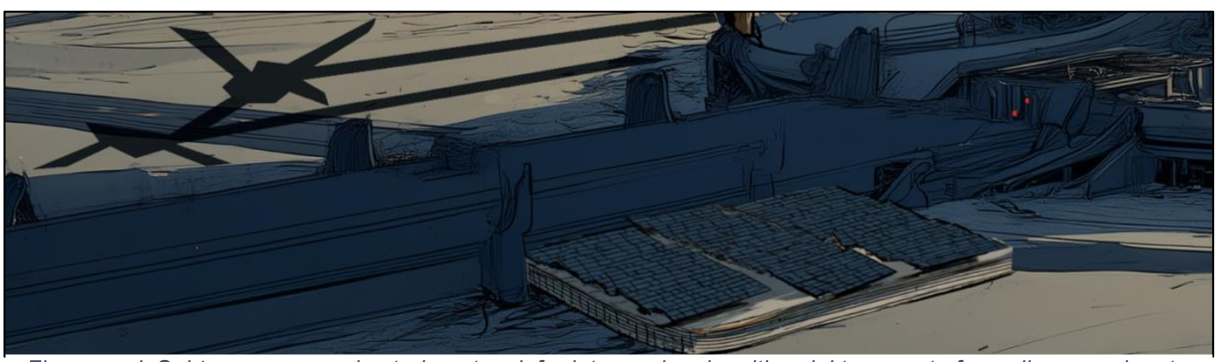

Figure xxxi: Subterranean maglev train network for inter-regional multimodal transport of supplies, people, etc. (Scenario #3)

TWh (Terawatt Hours) - Unit of energy equal to one trillion watt-hours, commonly used to measure large-scale energy production and consumption.

UAVs (Unmanned Aerial Vehicles) - Remotely piloted or autonomous aircraft systems for various operational applications.

UAS (Unmanned Aircraft Systems) - Complete systems including unmanned aircraft, control stations, and communication links.

Volumetric Displays - Three-dimensional display technology that creates images in true 3D space without requiring special glasses.

VR (Virtual Reality) - Immersive technology that creates completely artificial environments for user interaction.

Wetware Processors - Computing systems using biological materials such as synthetic neural tissues for information processing.

Zero-Carbon Aviation - Aviation operations that produce no net carbon dioxide emissions through the use of sustainable fuels, electric propulsion, or other non-fossil energy sources.

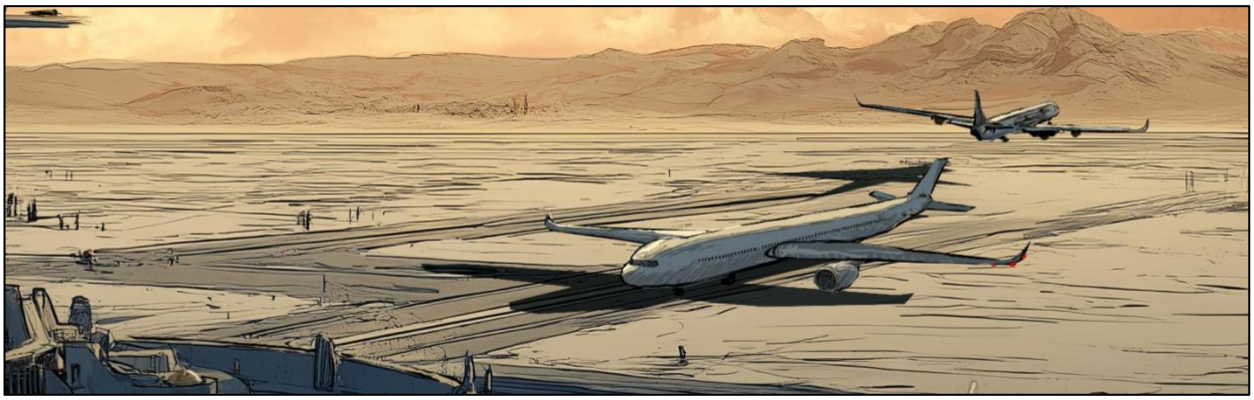

Figure xxxii: Limited, abandoned runways used for alternative purposes such as wind, solar or kinematic energy collection (Scenario #3).

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