NASA BLUE SKIES COMPETITION TECHNICAL REPORT

Sustainability and Connected Autonomy: A New Era for Aviation

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1 Introduction

In response to the increasing threat of climate change, NASA has declared that it aims to cut carbon emissions by half by 2050 compared to 2005, and achieve net zero emissions in 2060. To meet this goal, airports, airlines, and other organizations in the aviation industry will have to reduce emissions in a major way. Our paper focuses on how airports can be designed to support future changes in the aviation industry with a specific emphasis on two themes: airport sustainability and autonomy. Each theme is tied to our airport innovations and guided our final design of the airport.

To start, we modeled our initial concepts on the Denver International Airport. The new technologies we describe center around changes in aircraft form and fuel type, gate design, urban air mobility (UAM), storing multiple fuel types, and autonomous systems. Even though our concepts are applied to the Denver International Airport, we believe the designs can be generalized to other airports as well.

2 2050 Aviation Landscape

In 2050, we anticipate many changes to aircraft form and energy sources. We expect sustainable aviation fuel to be the largest proportion of the fleet followed by lesser proportions of hydrogen, ammonia, battery powered electric aircraft. We also expect aircraft form to adapt to new on-broad fuel storage requirements where one possible change is to a blended-wing body design. It is also likely that we will see supersonic commercial aircraft in the future. To support these aircraft, airports will require infrastructure changes in their gate design, aprons, and fueling and baggage loading.

Societal changes and attitudes toward flying may also have an impact on our airport design. If flying becomes cheaper and more accessible, then total air travel is likely to increase and in turn increase the urgency for sustainable aircraft [29]. Similarly, increases in the cost of jet fuel may make alternative fuel sources more attractive and speed up the transition. Expedited changes to sustainable aircraft may drive faster development of fuel storage locations, more aircraft operations vehicles, and expansive terminal layouts. If however, sustainable aircraft technology becomes costly to develop or support, then air travel will increase in cost and drive compromises to airport upgrades e.g. only supporting battery-electric aircraft and not hydrogen fuel.

3 Future Aircraft Fuel Sources and Design

3.1 Sustainable Aviation Fuel

Sustainable Aviation Fuel (SAF) is a carbon emission friendly alternative to jet fuel. SAF is similar in chemical composition to jet fuel, but, as opposed to requiring the extraction of new hydrocarbons, is manufactured from recycled carbon materials [22, 67, 55]. As a result, even though SAF generates CO2 during combustion, it is not adding more net CO2 to the environment [22]. SAF is also considered a "drop-in" fuel that can be mixed with jet fuel and does not require storage or engine modifications [75, 67, 56, 49]. The Federal Aviation Administration (FAA) currently allows commercial planes to fly with up to a 50% mixture of SAF [22, 56]. Both Los Angeles and Munich airports are currently configured to support SAF mixtures; additionally, several companies including Boeing, Rolls Royce, United Airlines, and General Electric are conducting SAF experiments with higher percentage mixtures [22, 60, 77].

However, there are several hurdles to widespread adoption of SAF. First, the US will need to expand available feedstocks to meet an estimated demand of 35 billion gallons on SAF in 2050 [22, 56, 70, 49]. Second, current production of SAF is limited to only a few facilities, but several thousand facilities will be required to meet future demand [22, 70]. Third, the cost per gallon of SAF is higher than jet fuel; while SAF prices may decrease over time, they may never be competitive with jet fuel [22].

Nevertheless, the Biden Administration, the FAA, and the Department of Energy have indicated that SAF will be key to achieving decarbonization goals [22, 55, 54, 70, 13, 33]. Not only does the fuel produce net-zero emissions, but SAF also does not require aircraft updates or significant airport infrastructure changes. As a result, we assume SAF production will increase and fuel a large proportion of the fleet in 2050.

3.2 Hydrogen Fuel

Hydrogen fuel, used in either combustion or as an electricity generating fuel cell, does not create CO2 emissions and can be considered a zero-carbon energy source if generated with renewable sources [2, 4, 13]. Hydrogen also contains more energy per kilogram than jet fuel. On the other hand, hydrogen is much less volume dense, up to a factor of 3000:1 when compared with jet fuel at standard temperature and pressure [2]. Pressurizing and cryogenic-cooling hydrogen can reduce volumetric density to a 4:1 ratio, which is more suitable for aviation [2, 13]. Nevertheless, aircraft design changes, such as a new blended wing-body design, are likely needed to accommodate large sophisticated hydrogen storage tanks [2, 13, 33, 46, 40]. Airbus, for example, is developing several hydrogen powered aircraft in their “ZEROe” program scheduled to debut in 2035 [2, 5]. ZeroAvia is also developing smaller and shorter range hydrogen fuel cell aircraft with a goal of commercial flights before 2030 [33, 78].

Three additional challenges to hydrogen fuel include establishing the required logistics of transporting, storing and distributing hydrogen at the airport [13, 66], reducing hydrogen generation costs [33], and public acceptance. While early hydrogen adoption at airports can be supplied with truck deliveries, pipelines will provide more reliable and safe fuel transportation for the long-term [46]. Safe storage of hydrogen is more complicated due to pressurization and cooling requirements and will likely require new infrastructure [65]. For distribution, airport trucks may be the best option over expensive costs to upgrade jet fuel hydrant systems [46]. Hydrogen is also currently several times more expensive than jet fuel and, to have a zero-CO2 lifecycle ("green hydrogen"), will require generation through electrolysis, which is costly and not yet implemented at scale [33, 46]. Finally, the introduction of a new fuel may require long-term engagement with the public to address concerns and reduce hurdles with public acceptance.

The pace of hydrogen aircraft development is uncertain. Some believe there will be faster rate of adoption of hydrogen aircraft [46], but we are more conservative due to the scope of the required technology innovations, likely aircraft design changes, and the subsequent FAA certification process [13, 33]. As a result, we believe hydrogen aircraft may be an emerging fuel source in 2050, but is unlikely to be a significant portion of the fleet.

3.3 Ammonia Fuel

Ammonia is another promising fuel source for aviation. Recent developments by Reaction Engines use heat to separate ammonia into an ammonia-hydrogen mixture which can be used for zero-carbon emission combustion in a jet engine [19]. Ammonia is often viewed as an alternative to hydrogen fuel due to its higher density per volume, see Figure 2, and higher boiling point [14, 24, 20]. A higher volumetric density may make it possible to retrofit current aircraft designs [19]. A higher boiling point for liquid ammonia also aids in simplifying fuel storage [14, 38, 20]. Additionally, ammonia production is already well established with 180 million tons produced annually [57, 23, 38, 20].

One disadvantage to ammonia fuel are possible environmental impacts. While ammonia promises zero carbon emissions, it may produce other air pollutants, such as nitrous oxide (NOx) [19, 14]. NOx can have negative environmental impacts and is believed to cause 16,000 premature deaths each year [14, 59]. Even though ammonia may only produce half as much NOx as jet fuel, hydrogen fuel would not produce any NOx emissions [24]. As a result, given the balance of benefits with environmental challenges of ammonia fuel and the early stage of technology development, we believe ammonia will be adopted in similar manner to hydrogen fuel.

3.4 Electric Aircraft

New advancements in battery technology are expanding to electric aviation. Companies such as Lilium, Kittyhawk, Beta, Archer and Joby Aviation are developing electric vertical takeoff and landing (eVTOLs) aircraft to serve as short range air taxis [44, 41, 15, 10, 39] and Airbus, Rolls Royce, and Eviation are researching fixed wing electric platforms [3, 62, 27, 42]. Even though electric aircraft produce zero-emissions, batteries have a low energy density relative to traditional fuels sources, see Figure 2 [72]. This leads to limited range and payload for future electric aircraft. Markets for electric aircraft still exist however, both in boosting urban mobility and serving short regional flights. Cape Air, for example, operates short range flights in New England and is purchasing Eviation's "Alice" all-electric aircraft for use in their routes [73, 35, 9]. Harbour Air in the Pacific Northwest serves a similar set of short range customers with their battery electric converted seaplanes [25, 32].

One challenge to electric aircraft is developing the required battery recharging infrastructure. Most airports are located near a power grid which can directly supply electricity; however, some airports in more remote locations likely need a local energy source, such as a system of solar panels [7]. Airports near a power grid may still require infrastructure upgrades, however, due to increased peak and total power demand from electric aircraft batteries [76, 43, 37]. Applying a battery-swap paradigm can reduce instantaneous energy demand and improve aircraft turn-around time, but will require a battery storage and charging location [76, 31]. Finally, standardization of charging infrastructure and installation at all airports, similar to passenger boarding bridges, is important for electric aircraft adoption [76].

In summary, even though the electricity grid is accessible at most airports, given the low energy density of near future battery technology, electric aircraft will be part of the near-term decarbonization solution but may only serve short distance flights.

3.5 Hybrid Electric Aircraft

We define hybrid electric aircraft as aircraft that have both batteries and combustible fuel and can implement a variety of different propulsion designs [61]. Specifically, we are interested in three designs: electric propulsion powered by batteries which can be recharged during flight with a fuel powered generator [18], electric propulsion powered by a gas turbine which can be augmented by batteries during periods of high power demand (e.g. during take-off) [63], and a mix of both electric and fuel propulsion [63]. Several companies are exploring hybrid electric aircraft including Electra, Embraer, Ampaire, Honeywell, Faradair and Rolls Royce [18, 17, 8, 36, 63, 61]. Early development trajectories indicate that hybrid electric aircraft will fill shorter range regional markets with passenger quantities similar to all electric aircraft [18, 17, 61]. Given the similarities in markets, technologies required and the active prototyping of hybrid electric aircraft today, we believe that hybrid electric aircraft will be adopted on a similar timeframe and in similar proportions to all-electric aircraft [18].

3.6 Aircraft Form

This section will discuss our anticipated aircraft design changes through the year 2050. We primarily considered modifications to traditional commercial airplanes and to Urban Air Mobility (UAM) vehicles. Additionally, the form of new aircraft will greatly depend on a newer approach to air travel. We expect commercial airplanes in particular to take an approach made up of high frequency, short distance flights. The planes will likely be more compact and, as a result, more aerodynamic. The changes to form will likely be supplemented with stronger, more sustainable materials [50].

The airplane form changes that have the most potential for the 2050 landscape are blended-wing body (BWB) and the strut-braced wing (SBW) designs. The SBW design of aircraft does not have many features that lend it to compatibility with the other feasible technologies we have identified, so we will be focusing on the BWB design as our primary advancement in aircraft form. The BWB design is simply a single connected wing with a payload area for passengers and/or cargo in the middle. The degree of blending between the wings and body can be manipulated to maximize efficiency and reduce noise pollution, supporting our overall goal. New designs rely on optimizing aerodynamics to reduce single-trip fueling frequency, which enables both long range flying and short range, high frequency flying [51]. The German Aerospace Center (DLR) is further researching the potential of a larger BWB design for passengers with an expected 2040 completion. These larger BWB designs rely primarily on hybrid fueling to support sustainability efforts and long range flying [29]. These designs can also be used for long range cargo transport for areas that cannot be reached by smaller UAMs. NASA and Boeing have already begun working on BWB concepts for commercial usage with the aforementioned qualities. Since BWB aircraft are already in use for military purposes, this may allow commercial airlines to pursue an amend-type certification from the FAA (3-5 years) versus an air-worthiness certification (5-9 years) [28].

In addition to the larger capacity provided by BWB aircraft, supersonic commercial airplanes may also be available. This design will benefit airport operations because passenger movement will flow quicker and the concept of short range, high frequency flying can be realized. However, supersonic aircraft need to overcome their structural and noise issues before mass adoption. On this front, Lockheed Martin's X-59 QueSST is a test aircraft being developed to resolve different issues with supersonic aircraft before it can be mass produced for commercial purposes [52].

4 Airport Innovations

4.1 Design Themes

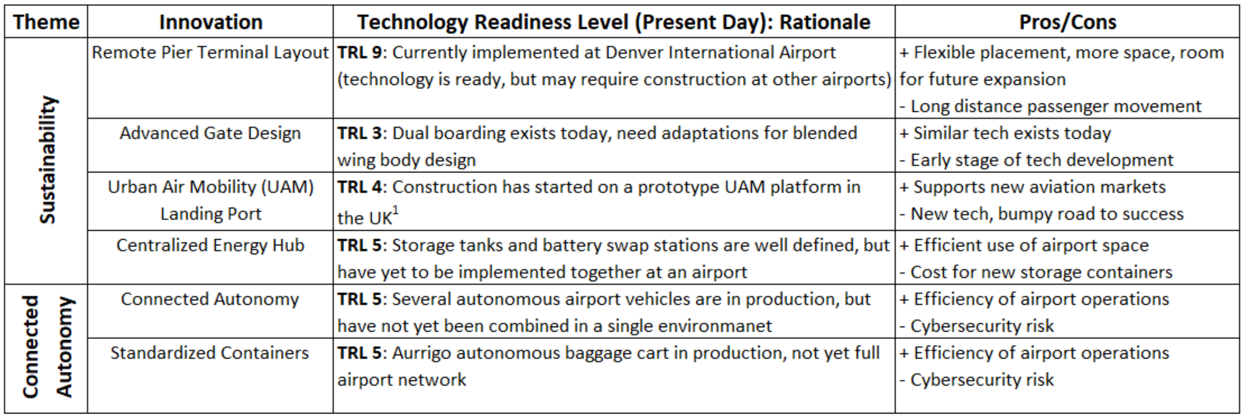
Our proposed innovations to airport design can be summarized by two themes: sustainability and connected autonomy. Sustainability focuses on two initiatives: first, supporting new aircraft through advanced terminal layouts and gate design, vertical landing ports, and centralized fuel storage; second, allowing for expansion of airport technologies and capacity to support increasing aviation demand. Our second theme, connected autonomy, is central to airport operations. We envision autonomous vehicles completing task across the airport such as moving baggage, food, fuel, passengers, etc. Each autonomous vehicle will be connected to a larger network to ensure safe movement and efficient operations. Both of our themes encompass how the airport of the future will adapt to new aircraft designs and increasing demand for air travel.

Each of the design innovations supporting our themes is discussed in detail in the following sections with a summary including estimated technology readiness levels (TRLs) provided in Table 1. Our TRL estimates are derived from NASA definitions as described in the Appendix, Figure 3.

4.1.1 Remote Pier Terminal Layout

After researching the different models for airport tarmac and terminal configurations, we believe that the remote pier (also called concourse) design would be the ideal model for airports of the future. The remote pier design maximizes apron use, as compared to pier and satellite designs, with arriving planes spending less time on the ground taxiing, waiting to refuel, and moving between gates. The system has also proved to be very efficient for handling passengers, but the distances between the terminal and the concourse necessitate the use of a sophisticated people-mover system [11].

Table 1: A summary of our design themes and innovations with an assessment of present day Technology Readiness Levels and Pros and Cons. (1. reference [71])



Theme	Innovation	Technology Readiness Level (Present Day): Rationale	Pros/Cons
Sustainability	Remote Pier Terminal Layout	**TRL 9**: Currently implemented at Denver International Airport (technology is ready, but may require construction at other airports)	+ Flexible placement, more space, room for future expansion - Long distance passenger movement
	Advanced Gate Design	**TRL 3**: Dual boarding exists today, need adaptations for blended wing body design	+ Similar tech exists today - Early stage of tech development
	Urban Air Mobility (UAM) Landing Port	**TRL 4**: Construction has started on a prototype UAM platform in the UK[1]	+ Supports new aviation markets - New tech, bumpy road to success
	Centralized Energy Hub	**TRL 5**: Storage tanks and battery swap stations are well defined, but have yet to be implemented together at an airport	+ Efficient use of airport space - Cost for new storage containers
Connected Autonomy	Connected Autonomy	**TRL 5**: Several autonomous airport vehicles are in production, but have not yet been combined in a single environmanet	+ Efficiency of airport operations - Cybersecurity risk
	Standardized Containers	**TRL 5**: Aurrigo autonomous baggage cart in production, not yet full airport network	+ Efficiency of airport operations - Cybersecurity risk

The remote pier design is also strategic as it can incorporate future updates to airport developments and aircraft changes. For example, hydrogen-powered aircraft may be slightly longer than traditional gate parking spaces [46] and BWB designs may be wider; a remote pier design will be readily adaptable to these changes. The remote piers can also be extended horizontally to add more gates for larger volumes of flights and passengers.

In the future, we will likely have an updated version of a shuttle running between the concourses, either under or above ground. This system will have to be highly efficient to get passengers to the farthest concourse in a reasonable amount of time. Since the concourses can also be very long, there will need to be a people-moving system within the airport as well.

4.1.2 Gate Design

When considering gate design, aircraft design will dictate the requirements. According to NASA's studies on blended wing-body aircraft, these planes can operate out of existing airport terminals [51]. These planes have a wingspan slightly larger than a Boeing 747, and cargo and passengers can utilize entrances at the front and rear of the aircraft. Because of the larger wingspan, it may be useful to have gates farther apart, or even designate two gates to a flight in order to facilitate more efficient boarding of the plane since there will be a much larger capacity for passengers available. There are already some flights that have multiple jet bridges to different entrances; this system is typically used to board first class and business class from separate entrances. This model can be used with blended wing-body aircraft as well.

4.1.3 Urban Air Mobility Landing Port

Urban Air Mobility (UAM) is a burgeoning mode of transportation for moving passengers over short distances, similar to a taxi and airports are a likely destination to support UAM infrastructure. To support UAM traffic, we envision a large landing area near the airport where passengers can disembark and proceed to the terminal. In terms of airport integration, the Denver International Airport's remote pier layout and large airport footprint can accommodate such a design with ease. There is space for the landing port and passenger transport to be located on the airport in a safe and operable location without interfering with other airport activities. The landing area would also require significant electrification infrastructure to meet UAM aircraft recharge requirements before departing. Autonomy plays a large role in the landing port area for the UAMs because many of the operations, like passenger transport and maintenance, do not have to be handled by human operators. Aside from passenger movement, UAMs can be used to handle small scale logistics transportation. Any shipments can be efficiently transported across the city without relying on road vehicles and traffic.

4.1.4 Centralized Energy Hub

Each of the possible future energy sources has different storage requirements. Our proposed innovation is to expand current jet fuel storage areas into a centralized, multi-fuel energy hub. In this configuration, jet fuel containers will remain in place and be used to store Sustainable Aircraft Fuel mixtures [56, 49]. Hydrogen will require new storage infrastructure to meet pressurization, cooling and safety requirements [65] and likely additional space due to its lower volumetric density [6]. Similar to hydrogen, ammonia is likely to be stored in a liquid state with specific requirements driving new infrastructure [38, 20, 26, 16]. The final component to the energy hub will be a battery recharge and swap center which will assist in faster aircraft turn around time by replacing aircraft batteries at the gate versus recharging [76, 31]. The depleted batteries can then be recharged at the battery storage facility for a future aircraft. Furthermore, this energy hub can be tied into an airport power generation facility that can be fueled by on-site solar power or hydrogen fuel and can help supplement contributions from the grid. In summary, new fuel types will require new infrastructure with associated costs; while most technologies are not new, they have yet to be implemented in a combined airport facility.

4.1.5 Connected Autonomy

We anticipate that the airport of the future will rely heavily on connected autonomous vehicles, which will conduct aircraft operations and routine tasks safely and efficiently. Several types of airport operations vehicles have autonomous prototypes in development including baggage trucks [12], snow plows [48, 47, 64], bird mitigation vehicles [68, 21] and even aircraft maintenance and preflight inspections [1, 30, 45]. To enable safe coordination, each autonomous vehicle will broadcast its position and activities to nearby vehicles and larger planning systems. Knowledge of the surrounding environment will prevent vehicle incidents and may also allow for more efficient vehicle movements instead of requiring a defined set of vehicle paths. Autonomous systems may also enable rapid decision making which may prove to be essential for supporting increased aviation demand.

Essential to a connected environment are fortified cybersecurity networks. The risks associated with adversary intrusion into autonomous airport vehicles could be catastrophic and, as a result, the airport network will require additional protection measures from exploits, viruses, and other ransomware. Cybersecurity protection measures may not always be a perfect solution and therefore a human presence will likely still be required in airport operations to respond in the event of an attack. This is essential for the safety of passengers and operators throughout the airport.

4.1.6 Standardized and Autonomous Logistics Containers

A specific subset of the connected autonomy innovation is the incorporation of standardized containers for baggage, packages, batteries, food, fuel etc. We envision that these containers will be battery or hydrogen powered and autonomous, similar to the design from Aurrigo [12] or Plug Power [34]. Standardization of the containers will allow for an efficient sequencing of payloads, e.g. bring food to an aircraft arrival, transport baggage back to the terminal, then transport new baggage from the terminal to another flight etc. These containers could also have their own automated entrances and exits to the airport terminal that are close to the gates so that there is minimal above-ground disruption where the planes are taxiing.

In the future, there may also be opportunities to airlift the logistics containers to decrease transit duration, for example bringing fuel or batteries from a distant storage location. The Defense Advanced

Research Projects Agency, Lockheed Martin, and Piasecki Aircraft were developing Aerial Reconfigurable Embedded System (ARES) vertical takeoff and landing (VTOL) unmanned aerial system to fill this function; however, the program was recently cancelled due to cost overruns and technical challenges [58, 74]. Nevertheless, this mode of transportation may be worth exploring in the future as technology matures.

4.2 Technology Development Timeline

The pace of implementation for each of our innovations is varied and dependent on both aircraft and infrastructure developments. Figure 1 summarizes our technology development timeline.

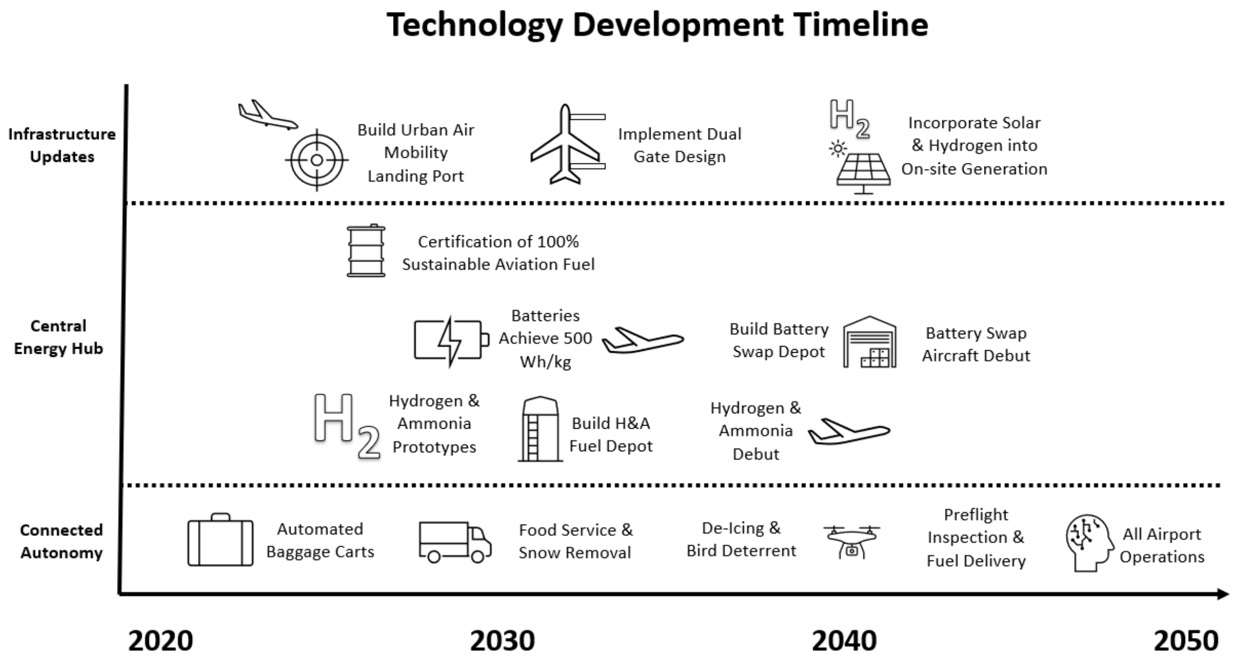


Figure 1: A technology development timeline for our airport design concepts. The pace of innovation is dependent on changes to aircraft and infrastructure.

5 Conclusions

To meet the 2050 sustainability goals set by organizations like NASA, airports will have to adopt similar themes of sustainability and autonomy. Our themes encompass a set of innovations including a new terminal layout and gate designs, an Urban Air Mobility landing port, a centralized energy storage, and a network of connected autonomous vehicles. Each of these design concepts are at a sufficient technology readiness level that they could be developed and available by 2050. The innovations also provide necessary improvements for new aircraft and are flexible in implementation and expansion. Although our innovations were initially based on applications to Denver International Airport, many of our recommendations can be applied to other airports. As a result, our concepts can be broadly applied to meet 2050 decarbonization goals.

6 Appendix

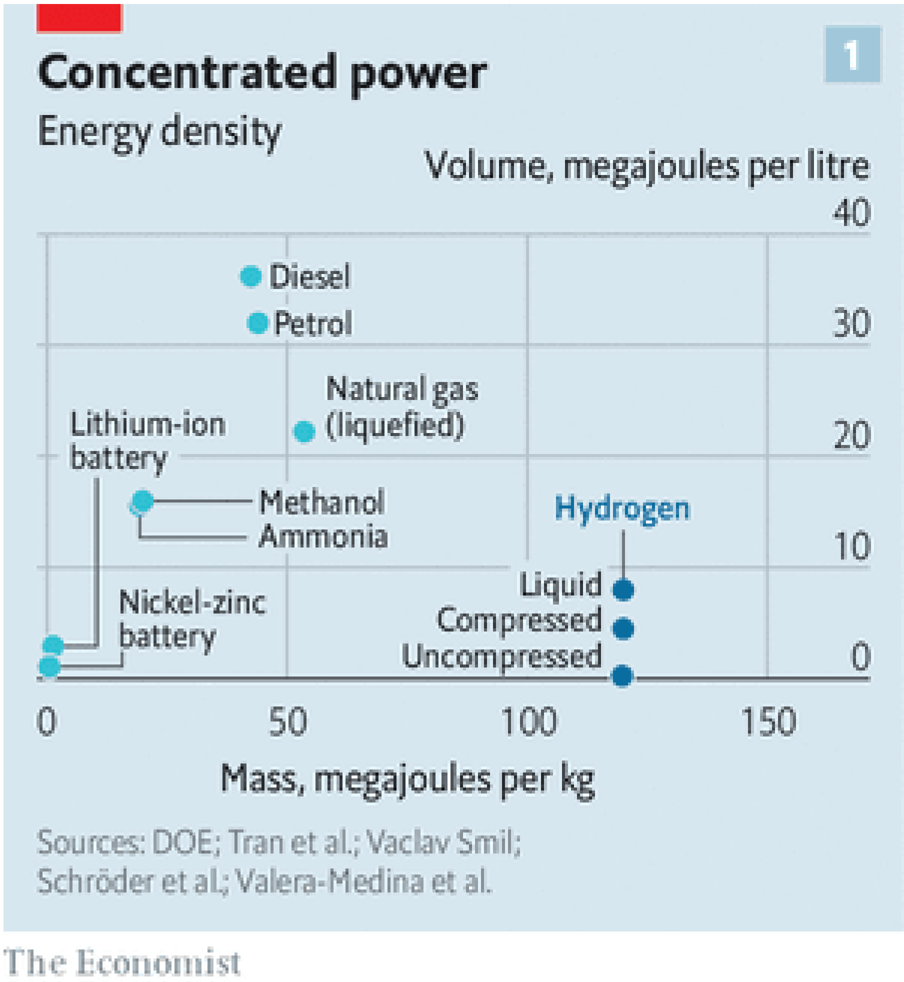


Figure 2: Comparison of the Energy Density of Fuel Sources [69]

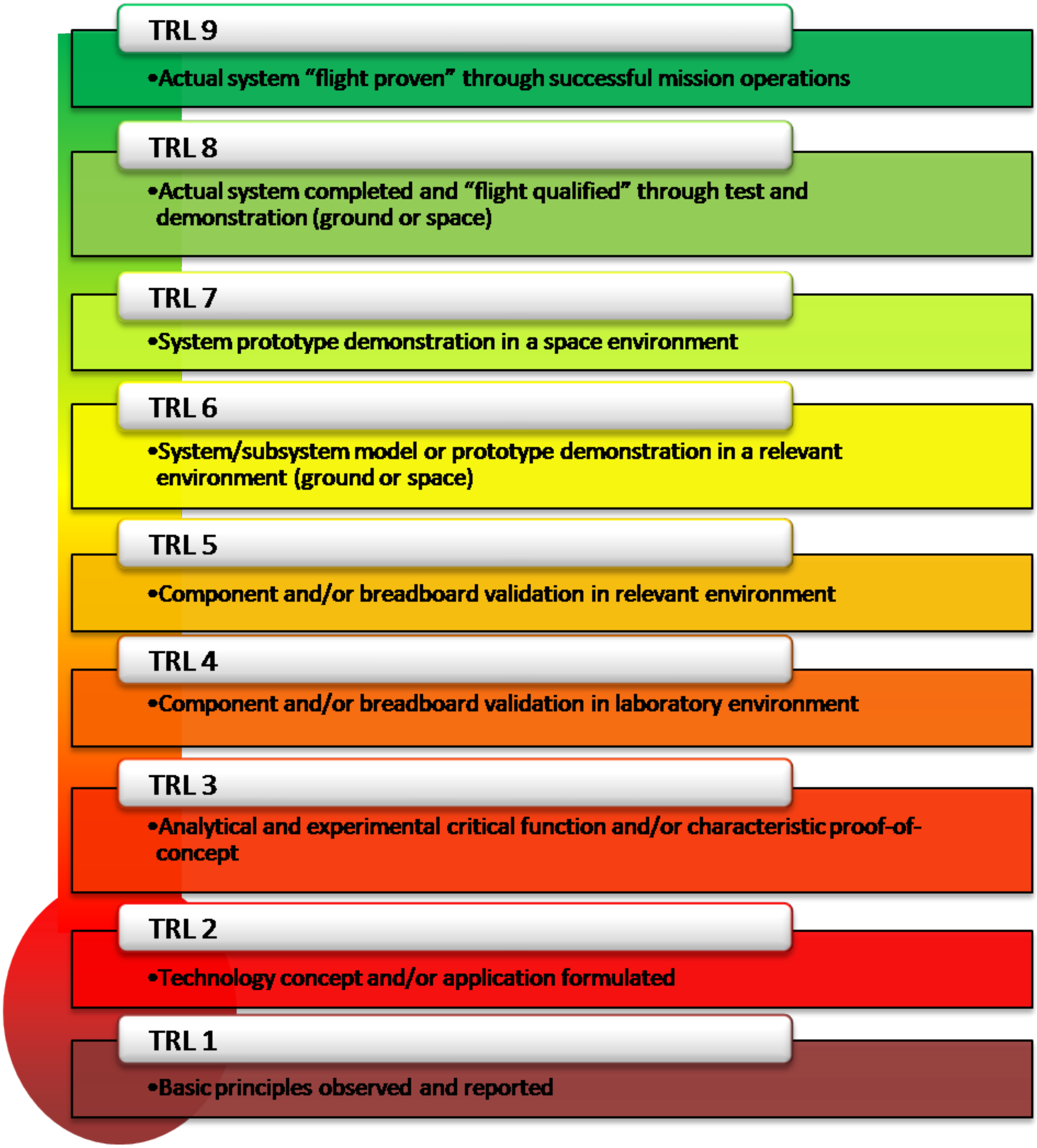


Figure 3: NASA Technology Readiness Definitions [53]

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