In collaboration with
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# Target True Zero: Delivering the Infrastructure for Battery and Hydrogen-Powered Flight

WHITE PAPER

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**Images:** Getty Images, Unsplash

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# Foreword

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The aviation sector stands at a critical moment in its history. Over the past century, its impact has been enormous. In connecting communities and helping drive economies across the planet, aviation has become woven into the fabric of our globalized world. However, these gains have consequences for our environment and the climate crisis.

Today, the sector faces a generational business opportunity to transform itself into a sustainable industry. Aviation has a long history of stepping up to challenges. It has continuously innovated in search of greater efficiencies. It has evolved new business models to adapt to changing realities. And it is positioned to embrace and deliver the historic long-term goal agreed by the International Civil Aviation Organization last year – to reach net-zero emissions from international aviation by 2050.

Meaningful progress has already been made towards sustainable aviation. Both government and industry are demonstrating an awareness of the issues that has begun to translate into strategic planning. The development and initial production of various Sustainable Aviation Fuels is underway. Aircraft efficiency shows ongoing improvements with each new generation, while flight paths and procedures are becoming ever-more streamlined. Research and development of new, zero-carbon propulsion systems and aircraft is well underway.

Yet there remains much more work to be done. There is no silver bullet to deliver sustainable aviation. The sector will need to develop and deploy a broad range of solutions, especially given the significant uncertainty around the technical performance and economic viability of the current alternatives.

New, zero-emissions, alternative propulsion technologies hold out the promise of helping reduce the climate impact of aviation – although the journey to realize the full potential of these technologies is only just beginning. Fortunately, progress is swift and accelerating. This year has already witnessed two records fall for the largest passenger flights ever powered by hydrogen. But along this journey to net zero, there is still so much to do to take these technologies beyond initial prototypes and build the new businesses that will transform aviation.

This report focuses on the infrastructure that will be needed to unlock zero-carbon propulsion technologies for aviation. Getting infrastructure right will be critical in allowing this new industry to take off – whether that means "on-airport" infrastructure, such as chargers and refuellers, or "off-airport" infrastructure, such as producing enough green electricity.

By helping to reduce the uncertainty that the shift to alternative propulsion will entail, this report aims to support policy-makers and leaders in the private sector to make informed decisions. There is a great deal at stake in getting this transition right. Collaboration across geographies, industries and stakeholders is critical to fast-track aviation's trajectory towards a more sustainable future.

# Executive summary

## New types of infrastructure will be essential for supporting battery and hydrogen-powered aircraft that will begin operating this decade.

As the quest for solutions to tackle the climate impact of aviation becomes more urgent, the focus is sharpening on the role of alternative propulsion technologies such as hydrogen, battery-electric and hybrid-electric aircraft. By some estimates, aircraft running on hydrogen and battery-electric powertrains could make up 21-38% of the global commercial and cargo aircraft fleet by 2050.[1]

While this timeline may feel distant, these new technologies will begin appearing this decade, requiring new types of ground infrastructure to deliver the green hydrogen and electricity these aircraft will need. At present, however, there is a lack of understanding about what such infrastructure changes entail and how airports and other stakeholders can begin to prepare for them.

This report, produced by Target True Zero – a World Economic Forum initiative bringing together leaders from across the aviation and aerospace industries, with support from knowledge partners McKinsey & Company, the University of Cambridge's Aviation Impact Accelerator and the Aviation Environment Federation – aims to shine a light on some of the key considerations affecting alternative propulsion, as part of Target True Zero's goal of accelerating the development and deployment of electric and hydrogen aircraft.

**The report addresses three dimensions of the challenge: infrastructure, investment and collaboration.** Chapter 1 identifies the energy requirements to support alternative propulsion at both the global and airport level by 2050, and what infrastructure this translates to. Chapter 2 explores what these requirements mean in terms of the level and timing of investments. Chapter 3 analyses how collaboration will be needed to deliver appropriate infrastructure across the aviation and other sectors.

**The report's findings are built on 10 key insights** developed through McKinsey & Company analysis, informed by workshops and conversations with industry leaders held by Target True Zero:

1. Global demand for **alternative propulsion could require 600-1,700 TWh of clean energy** by 2050. This is equivalent to the energy generated by around 10-25 of the world's largest wind farms, or a solar farm half the size of Belgium.
2. **Large airports could consume 5-10 times more electricity by 2050** than they do today, to support alternative propulsion.
3. Alternative propulsion will require **two new infrastructure value chains** – one for battery-electric aviation and one for hydrogen – which may include a whole variety of new partners that are not currently part of the aviation ecosystem.
4. **Most airports have space for hydrogen liquefaction and storage infrastructure,** but not enough land to generate all of the clean energy needed to power battery-electric and hydrogen aircraft.
5. Shifting to alternative propulsion will require a **capital investment of between $700 billion and $1.7 trillion** across the value chain by 2050. Approximately 90% of this investment will be for off-airport infrastructure, primarily power generation and hydrogen electrolysis and liquefaction.
6. Investment needed for airport infrastructure will be significantly higher for large airports than for smaller airports, but of **similar magnitude to other major investments such as building a new terminal**.
7. **Costs to operators of alternative propulsion are expected to be around 76-86% over the market price for green electricity** – reflecting additional aviation infrastructure operating costs.
8. The investments needed to meet 2050 goals must start now. The first elements of **on-airport infrastructure must be in place by 2025** to meet expected energy demand.
9. To harness the power of network effects and regional connectivity, **coordination of infrastructure investment** will be required to make alternative propulsion operations feasible.
10. The aviation industry will need to **partner with other industries to secure enough green electricity and hydrogen** in a supply-constrained environment and have a voice in shaping the future of the hydrogen ecosystem.

With these findings, Target True Zero plans to identify how it can further work with key stakeholders to deliver the infrastructure changes that are needed to support the alternative propulsion ecosystem.

# Introduction

## Planning for infrastructure needs to begin now, to prepare for the arrival of the first battery and hydrogen-powered aircraft this decade.

Aviation accounts for about 2% of global carbon dioxide ($CO_2$) emissions, but its overall contribution to climate change is believed to be significantly higher when non-$CO_2$ emissions are considered.[2] This percentage is likely to grow considerably as other sectors decarbonize. In search of solutions to this problem, the industry has taken the first steps towards embracing sustainable aviation fuel (SAF) – a drop-in hydrocarbon fuel that can reduce lifecycle emissions. Given the scale of the problem, however, attention has also begun to focus on the role of new, alternative propulsion technologies – such as battery and hydrogen-powered aircraft – that don't rely on carbon at all.[3]

To help build consensus around the role that alternative propulsion can play in decarbonizing the sector and to accelerate the development and deployment of key aircraft technologies, the World Economic Forum has established the Target True Zero coalition to bring together key leaders in this space, complementing the work of the Forum's Clean Skies for Tomorrow coalition to scale-up the use of SAF. Target True Zero's first report, published in July 2022, detailed the potential of three battery and hydrogen-powered technologies for reducing the sector's climate impacts:[4]

– **Battery-electric**: Batteries can be used to power electric motors, which then drive a propeller directly. Battery-electric aircraft would eliminate all in-flight emissions[5] – with their range forecast to be up to 400 km in 2035 and potentially rising to 600 km in 2050.

– **Hydrogen fuel cell electric**: Fuel cells can be used to convert hydrogen and air into water and electricity. Hydrogen fuel cell aircraft would eliminate nearly all in-flight emissions[6] – but they could release water vapour at altitude that could lead to the formation of climate-warming contrails.[7] Nevertheless, hydrogen fuel cells could allow electric aircraft to be designed with a much longer range than those powered by batteries – potentially providing a fuel cell aircraft with a range of around 2,000 km by 2030 and up to 4,000 km by 2035.

– **Hydrogen combustion**: Liquid or gaseous hydrogen can be combusted in a gas turbine in the same way that jet fuel is today, and it may be possible to design a hydrogen combustion aircraft that operates over the same distance as existing long-haul airliners by 2035. Hydrogen combustion aircraft would eliminate $CO_2$ and soot emissions in-flight, but would still produce nitrogen oxides (NOx). The degree to which these could form climate-warming contrails means there is uncertainty about the overall climate impact of this technology.

By some estimates, these alternative propulsion aircraft (and hybrid variations of them) could make up over one-third of all aircraft in operation by 2050.[8] While this may seem like a distant timeline, the first commercial aircraft powered by alternative propulsion could be flying by the mid-2020s, with a multitude of companies working to bring these aircraft to market in response to pressure from customers (operators and passengers), investors and the changing regulatory landscape. These developments can be seen across all segments of the aviation sector:

– **Advanced Air Mobility**: There are hundreds of designs for electrical vertical take-off and landing (eVTOL) aircraft which would carry a small number of passengers short distances – such as from city centres to airports or between nearby cities. These new technologies will enable what is known as Advanced Air Mobility (AAM) or Urban Air Mobility (UAM) and can either be viewed as an extension of the existing aviation sector or as a new industry entirely. Manufacturers of the first passenger-carrying eVTOL aircraft are aiming to certify these from as early as 2024.[9]

– **Regional aviation**: These are the shortest-range flights currently considered as commercial aviation and typically cover routes of less than 800 km. A number of solutions are being developed, including fully electric aircraft, hybrid-electric aircraft and the retrofit of existing smaller aircraft with hydrogen fuel cell technology. All of these could be operating commercially by the second half of this decade.[10]

– **Larger and longer-range**: Retrofitted aircraft with hydrogen fuel cells are planned from the beginning of the next decade, while clean-sheet designs of new hydrogen propulsion aircraft – including those powered by hydrogen combustion engines – could be seen by the mid-2030s.[11]

FIGURE 1 **Timeframes to adopt alternative propulsion, by technology up to 2050**

## The Mission Possible Partnership (MPP) prudent scenario estimates alternative propulsion penetration of 21% by 2050 vs. 38% for the optimistic scenario

Adoption timeline from MPP, % of global aircraft fleet

MPP Prudent scenario   MPP Optimistic scenario

### Battery-electric

**Expected market niche in 2050:**

Regional air mobility, currently served by turboprops and short regional jet flights (e.g. ATR42, Embraer E175) Battery-electric (BE) aircraft are expected to be limited to regional and narrow-body flights <500 nm.

### Hydrogen combustion

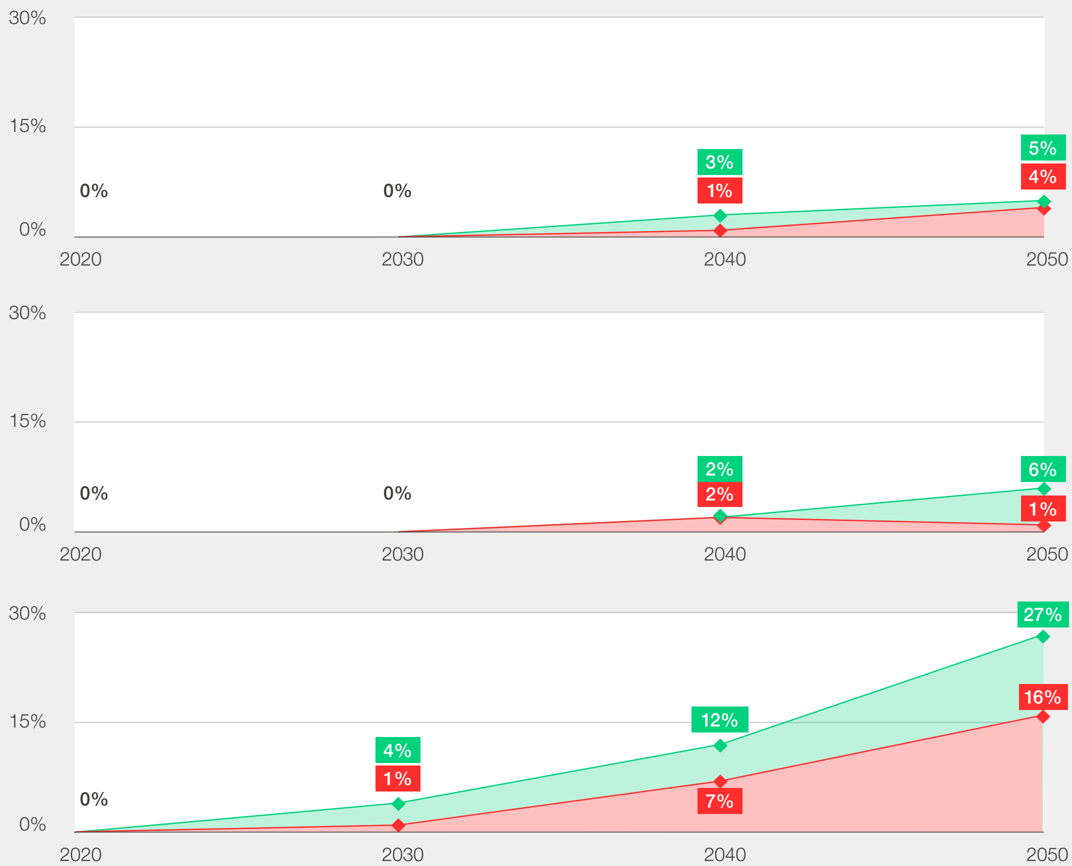
**Expected market niche in 2050:**

Narrow-bodies (e.g. Boeing 757, Airbus A321)

### Hydrogen fuel cell

**Expected market niche in 2050:**

Smaller narrow-bodies and regional jets (e.g. Airbus A220, Embraer E195)




**Notes:** Adoption timeline based on the Mission Possible Partnership's *Making Net-Zero Aviation Possible* report, with adoption driven by technological readiness and forecasted total cost of ownership (TCO).

Under the MPP scenarios, by 2050 conventional aircraft are expected to make up 62-79% of the global fleet – and 82-97% of wide-body aircraft. In order to meet the industry's net-zero targets, these aircraft will need to be primarily fuelled by sustainable aviation fuels which provide 65-85% of the industry's overall energy use in the MPP scenarios.

**Sources:** McKinsey & Co., adapted from Mission Possible Partnership, *Making Net-Zero Aviation Possible*, July 2022.

Ensuring the required infrastructure is in place to operate these aircraft is going to be critical to their success. This means not only new physical infrastructure at airports, such as hydrogen storage tanks and battery charging stations, but also vast amounts of green energy to ensure that these new technologies reduce the sector's emissions rather than simply transferring them to upstream power generators.

Some of the considerations airports and other stakeholders will need to think about include: how they are sourcing this green energy, implications for their electricity grids, the levels of investment required and the impacts on day-to-day operations – as well as how new businesses across the value chain can be built and scaled-up to support these new types of aircraft. While these implications are not yet fully understood, planning for them will need to begin now to accommodate the first generation of alternative propulsion aircraft and to ensure they reach the potential they offer for decarbonizing the sector.

This report builds on the previous Target True Zero work to help provide insights and quantify some of the key requirements related to alternative propulsion infrastructure, to allow airports and other stakeholders to begin making informed decisions for the future.

In order to analyse what infrastructure will be needed to support alternative propulsion, the report draws insights based on traffic forecasts from the Aviation Transition Strategy of the Mission Possible Partnership (MPP).[12] While different forecasts exist around the speed and extent to which battery and hydrogen-powered aircraft will appear in the fleet, MPP's analysis is based on an assessment of how the industry can reach net-zero emissions by 2050. It therefore represents the level of ambition needed if aviation is to meet the 2050 goals set by both the global industry and the International Civil Aviation Organization (ICAO).[13]

As alternative propulsion technologies continue to mature, it can be expected that these will make up ever larger parts of the aviation fleet's energy mix. So although this report is intended to provide airports and stakeholders with information to help them begin making decisions about alternative propulsion aircraft, there will be further investments required beyond the scope of 2050 that are not quantified in this paper.

This report makes use of four airport archetypes to understand how alternative propulsion infrastructure could develop under different scenarios (see Figure 2). The scope of this report has been limited to upgrades to infrastructure required for traditional aviation services that operate from airports. While eVTOLs and other AAM technologies may make use of electric charging or other facilities at airports in the future, they will also require very different types of infrastructure such as "vertiports" in urban areas which are not addressed within this paper.

The four airport archetypes used in this report are:

– **Intercontinental hubs**, which comprise roughly the 40 largest commercial and cargo airports in the world, such as UK's London Heathrow and Changi in Singapore.

– **Major regional airports**, comprising approximately 200 medium-sized airports acting as domestic hubs, such as Hamburg in Germany or Ronald Reagan Washington National Airport in the US.

– **Small regional airports**, including all other airports with regularly scheduled services that act primarily as spokes in the larger aviation network.

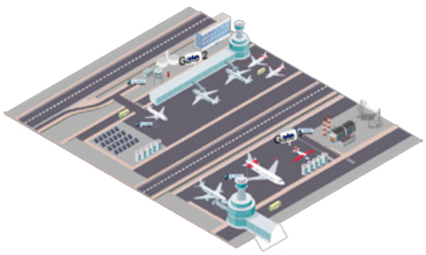
– **Municipal airports**, which support exclusively general aviation aircraft (for private transport and recreation).

FIGURE 2 | **Four airport archetypes (2050 forecasts)**

## Intercontinental hub (e.g. Singapore Changi)

| Traffic volume | | |
|---|---|---|
| | Daily seats | 182,135 |
| | Daily flights | 2,534 |

| Flights by aircraft type | | |
|---|---|---|
| | Wide-bodies | 238 |
| | Narrow-bodies | 690 |
| | Regional jets | 128 |
| | Turboprops | 14 |
| | General aviation | 53 |
| | Urban air mobility | 1,410 |



## Major regional airport (e.g. Hamburg Airport)

| Traffic volume | | |
|---|---|---|
| | Daily seats | 53,046 |
| | Daily flights | 768 |

| Flights by aircraft type | | |
|---|---|---|
| | Wide-bodies | 34 |
| | Narrow-bodies | 255 |
| | Regional jets | 31 |
| | Turboprops | 20 |
| | General aviation | 96 |
| | Urban air mobility | 332 |

## Small regional airport (e.g. Palmas Airport, Brazil)

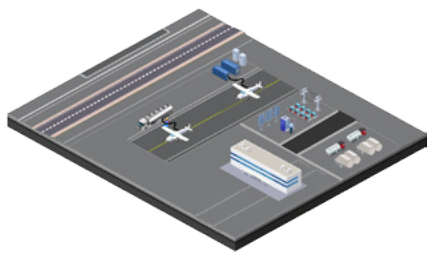
| Traffic volume | | |
|---|---|---|
| | Daily seats | 1,670 |
| | Daily flights | 101 |

| Flights by aircraft type | | |
|---|---|---|
| | Wide-bodies | 1 |
| | Narrow-bodies | 9 |
| | Regional jets | 2 |
| | Turboprops | 4 |
| | General aviation | 77 |
| | Urban air mobility | 8 |

## General aviation airports

| Traffic volume | | |
|---|---|---|
| | Daily seats | – |
| | Daily flights | 32 |

| Flights by aircraft type | | |
|---|---|---|
| | Wide-bodies | 0 |
| | Narrow-bodies | 0 |
| | Regional jets | 0 |
| | Turboprops | 0 |
| | General aviation | 32 |
| | Urban air mobility | 0 |



**Source:** McKinsey & Co.

Throughout this report, a distinction is made between “on-airport” and “off-airport” infrastructure costs. While exceptions will exist, on-airport infrastructure costs are those most likely to be covered by airports, including a portion of hydrogen liquefaction, as well as liquid hydrogen storage, mobile refuelling, hydrants and other airport infrastructure. Off-airport infrastructure includes the means to generate most of the green electricity needed for hydrogen electrolysis and liquefaction – processes that are more likely to occur in non-airport locations.

While airports will be the most visible stakeholder in terms of delivering infrastructure for alternative propulsion, they cannot do this alone. Collaboration will be needed across the aviation sector as well as with stakeholders in adjacent sectors and the wider renewable energy ecosystem.

This report has been produced through workshops and discussions held by the World Economic Forum’s Target True Zero coalition with industry experts on the challenges that will need to be overcome to deliver infrastructure for alternative propulsion. This paper focuses on the high-level decisions airports will need to make about which investments are required, when they need to be made, and what is needed in terms of the wider ecosystem. There will also be challenges for airports related to the operational aspects of alternative propulsion aircraft (e.g. potentially longer turn-around times, the need to support fleets running on different fuels), which Target True Zero plans to address during future stages of its work.

**The report addresses three dimensions of the challenge: infrastructure, investment and collaboration.** Chapter 1 identifies the energy requirements to support alternative propulsion at both the global and airport level by 2050, and what infrastructure this translates to. Chapter 2 explores what these requirements mean in terms of the level and timing of investments. Chapter 3 analyses how collaboration will be needed to deliver appropriate infrastructure across the aviation and other sectors.

# 1 Infrastructure for the shift to alternative propulsion

On- and off-airport infrastructure will largely be determined by the overall energy requirements for alternative propulsion.

Alternative propulsion will need to be supported by both green energy and appropriate infrastructure to deliver this energy to the aircraft. This chapter identifies the overall energy requirements for alternative propulsion and what this means for the physical infrastructure that will need to be provided.

## 1.1 Energy requirements for alternative propulsion

For alternative propulsion to reduce lifecycle emissions from aviation, it is going to require clean energy – renewable or low-carbon electricity and green hydrogen – to power the aircraft using these technologies. While the energy demands of battery or hydrogen-powered aircraft will depend on the extent to which they are adopted in coming decades – currently unknown – the resulting energy demands could be extremely high.

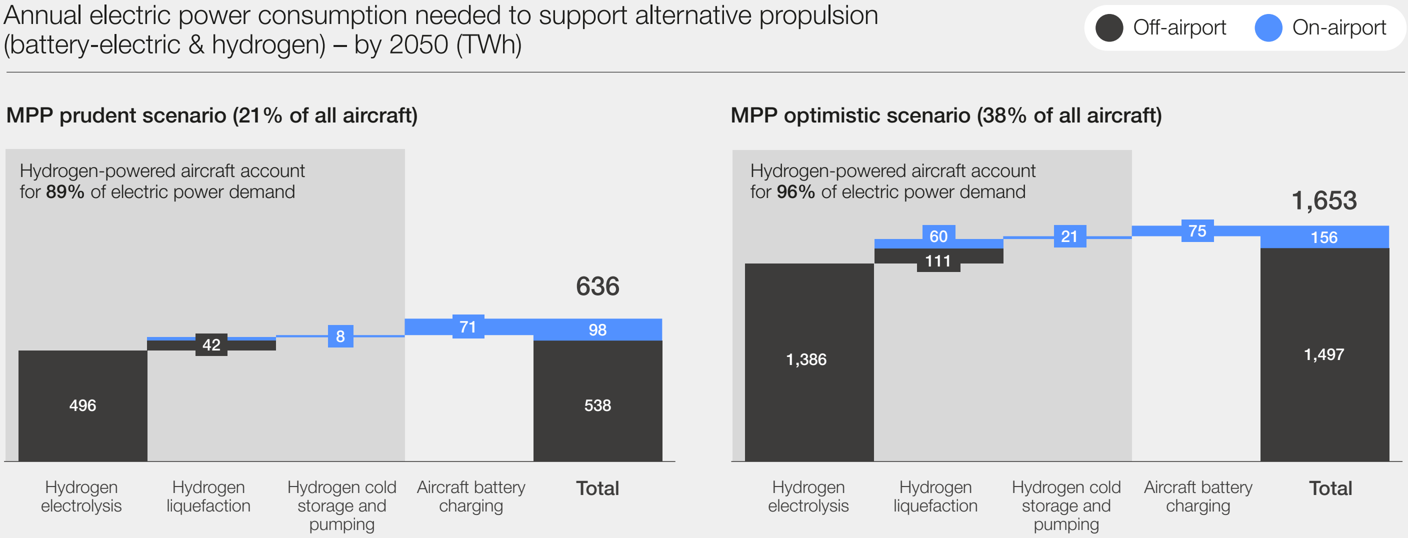
The MPP's Aviation Transition Strategy – developed by the World Economic Forum and other stakeholders – identifies a range of scenarios for the adoption of different propulsion technologies required for the industry to reach net-zero emissions by 2050. The prudent and optimistic scenarios from that work are used as the basis of the analysis in this paper. Under these scenarios, battery-electric and hydrogen powered aircraft are forecast to make up between 21% and 38% of all aircraft by 2050, or 15-34% of the sector's overall energy needs. As illustrated in Figure 3, under these scenarios, alternative propulsion could require between 600 and 1,700 TWh of clean energy by 2050, globally – equivalent to the energy generated by around 10-25 of the world's largest windfarms or a solar farm the size of Belgium.[14] The vast majority (89-96%) of this will be used for hydrogen-powered aircraft, while only 4-11% will be used to power battery-electric aircraft, which are expected to be smaller aircraft (e.g. turboprops, regional jets, smaller narrow-bodies).

**Insight 1:**
Global demand for alternative propulsion could require between 600 and 1,700 TWh of clean energy by 2050. This is equivalent to the energy generated by around 10-25 of the world's largest wind farms, or a solar farm half the size of Belgium.

## FIGURE 3 Forecast energy demand for alternative propulsion under Mission Possible Partnership prudent and optimistic scenarios

Annual electric power consumption needed to support alternative propulsion (battery-electric & hydrogen) – by 2050 (TWh)

**MPP prudent scenario (21% of all aircraft)** | **MPP optimistic scenario (38% of all aircraft)**




**Note:** International hub airports are assumed to have onsite hydrogen liquefaction infrastructure.
**Source:** McKinsey & Co.

Under either scenario illustrated in Figure 3, approximately 90% of this electric power will be consumed by hydrogen electrolysis, which is expected to take place off-airport given the scale of power generation required. Nevertheless, while requirements will differ depending on the type of airport in question, airports are going to consume more energy for their on-site operations than they do today. The demands will be biggest for intercontinental hubs and major regional airports which will need to support larger hydrogen aircraft.

In the case of a large hub airport looking to invest in its own highly energy-intensive onsite hydrogen liquefaction, as well as charging for battery-electric aircraft, total onsite electricity consumption (including for terminal, ground support and other uses) could be between 1,250 and 2,450 GWh per year – about 5-10 times more electricity than London Heathrow currently consumes.[15] To meet these demands, airports will need to take steps to upgrade grid connections, local power distribution infrastructure and their own power stations.

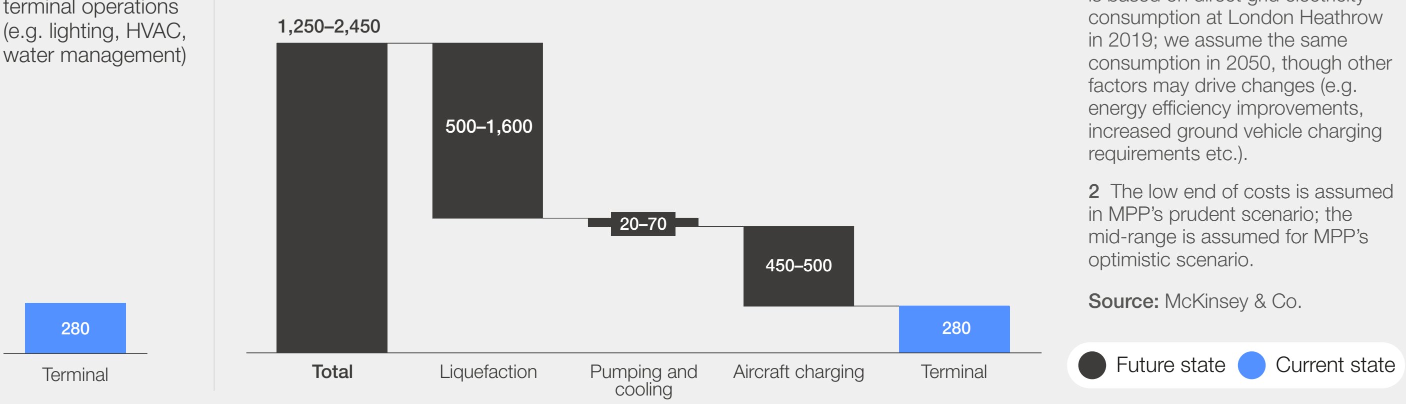
**Insight 2:**
Large airports could consume 5-10 times more electricity by 2050 than they do today, to support alternative propulsion.

## FIGURE 4 Impact of energy consumption for large airports

Electricity consumption at a typical intercontinental hub, GWh per year

**Current state:** airports consume electricity for terminal operations (e.g. lighting, HVAC, water management)

**Future state:** airports could consume 5-10 times more electricity to support alternative propulsion




**Notes:**

**1** The terminal figure (280 GWh/yr) is based on direct grid electricity consumption at London Heathrow in 2019; we assume the same consumption in 2050, though other factors may drive changes (e.g. energy efficiency improvements, increased ground vehicle charging requirements etc.).

**2** The low end of costs is assumed in MPP's prudent scenario; the mid-range is assumed for MPP's optimistic scenario.

**Source:** McKinsey & Co.

## Impact of energy requirements on the alternative propulsion value chain

With a grasp of the energy requirements for alternative propulsion, it is possible to begin to understand the different roles airports and other stakeholders will need to play in delivering this infrastructure. This in turn will involve understanding what the new value chain for alternative propulsion looks like.

Alternative propulsion will require two new infrastructure value chains – one for battery-electric aviation and one for hydrogen – which may include a whole variety of new partners that are not currently part of the aviation ecosystem. These value chains will need to coexist with the infrastructure required for SAF and conventional fuel. The sector will need new procedures for energy acquisition, storage, processing and management, as well as the means to distribute that energy to aircraft, as summarized below and in Figure 5:

**Battery-electric**: the generation and delivery of clean energy, along with energy storage and management, will likely require the following:

- Upgrades to grid infrastructure
- Direct-charging stations at airports or battery-swapping systems for the distribution of energy to aircraft

**Hydrogen**: there are several possible models. Aviation will likely be more reliant on liquid than gaseous hydrogen, given that it takes up less space and is therefore better suited as an aircraft fuel. Different models for providing airports with liquid hydrogen and associated refuelling challenges include the following:

- Liquefaction of hydrogen offsite, which is then delivered to the airport
- Delivery of gaseous hydrogen to the airport, which is liquefied onsite
- Onsite production (likely very limited) and liquefaction
- Storage and distribution of liquid hydrogen (which must be kept at temperatures below 240°C) will present unique challenges for airports, requiring robust energy management and safety systems. Depending on the size of the airport and the types of aircraft in operation, airports may use mobile fuelling bowsers, which could include modular tanks of hydrogen that can be installed and uninstalled directly from the aircraft, or an underground hydrant system for dispersing hydrogen.

**Insight 3**:
Alternative propulsion will require two new infrastructure value chains – one for battery-electric aviation and one for hydrogen – which may include a whole variety of new partners that are not currently part of the aviation ecosystem.

FIGURE 5 | **Summary of alternative propulsion value chains**


**Source:** McKinsey & Co., adapted from Connected Places Catapult, *The Roadmap to Zero Emission Flight Infrastructure*, April 2022.

## 1.2 Impact on airport infrastructure

While airports have been touted as possible energy hubs, the scale of energy demand for alternative propulsion noted above means it will be extremely challenging for all energy production to be performed onsite at airports. For instance, if Paris Charles De Gaulle Airport (see Figure 6) is used as an example of a major international hub, it would require approximately 5,800 hectares of solar panels to generate sufficient electricity to meet its demands under the MPP's prudent scenario – to power the electrolysis, liquefaction, storage and pumping of liquid hydrogen and to charge battery-electric aircraft. This space far exceeds the size of the airport itself which is 3,300 hectares today.[16]

As a result of these requirements, it is likely that airports will be reliant on partnerships with other electricity providers within their regional ecosystems. There may, nevertheless, be opportunities for some onsite electricity generation, while some onsite storage may be needed to power terminals or charge battery-electric aircraft. But each airport's situation will be unique and will depend on its energy strategy. For example, if Paris Charles De Gaulle Airport were to buy less-costly electricity overnight and then store enough to cover 50% of the energy required for battery-electric flights, it would only require around two hectares of land for its energy storage system, which could probably be accommodated onsite.

While it is expected that most of the energy generation for alternative propulsion will be performed off-airport due to space constraints, the actual processes reliant on this energy would require much less land and could therefore be located on-airport. For instance, it is estimated that – to support alternative propulsion at the levels consistent with the MPP scenarios in 2050 – Charles De Gaulle would need 1-12 hectares of space for the hydrogen electrolysis process and 3-12 hectares for hydrogen liquefaction and storage. However, due to economic and efficiency reasons these processes could occur offsite and it is likely this would be the case for electrolysis in particular.

> **Insight 4**:
> Most airports have space for hydrogen liquefaction and storage infrastructure, but not enough land to generate all of the clean energy needed to power battery-electric and hydrogen aircraft.

FIGURE 6 **Case study of airport land requirements – Paris Charles De Gaulle Airport**

### New land-use needs at a typical intercontinental hub

**$H_2$ liquefaction and storage** (3–12 ha)

Can likely be built on airport property

**$H_2$ electrolysis** (1–12 ha)

Can likely be built on airport property

**Solar power generation** (5,800–23,000 ha)

Will require off-airport facilities

**MPP Prudent scenario**
232 x 25 ha squares

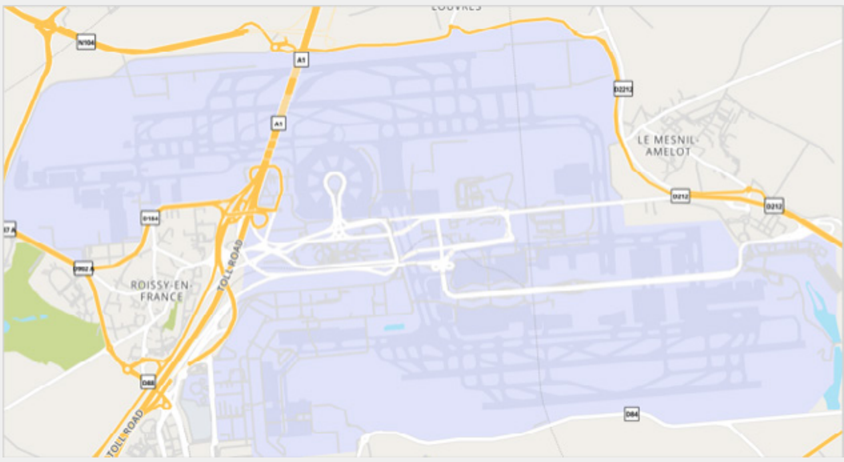
**MPP Optimistic scenario**
920 x 25 ha squares

### Paris Charles De Gaulle Airport
(land area: ~3,237 ha)

25 ha square (0.25 km²) – to same scale as map of airport below

500 m

3–12 ha   1–12 ha




**Land required for infrastructure increases proportionally to air traffic (i.e. energy required)**

**Source:** McKinsey & Co.

Informed by these insights, Figures 7 and 8 provide high-level overviews of what such infrastructure requirements would mean for a "day in the life" of both hydrogen-based (fuel cell and combustion) and battery-electric airport infrastructure.

FIGURE 7 **A day in the life of hydrogen-based airport infrastructure**

## For hydrogen-powered aircraft, an airport can acquire hydrogen in various ways or produce it itself onsite

### Liquid $H_2$ delivered to airport:

Cryogenic tanker trucks deliver liquid hydrogen to the airport. They connect with a refuelling pipe to offload hydrogen into storage tanks.

### Gaseous $H_2$ delivered to airport:

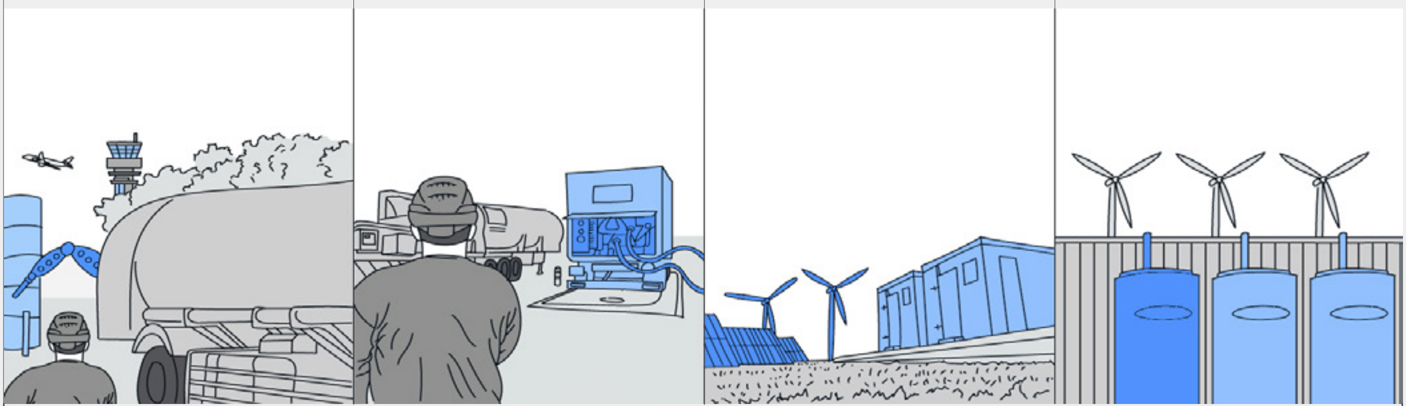
Gaseous hydrogen is brought to the airport by a pipeline or tube trailer truck.

### Gaseous $H_2$ produced at airport:

Gaseous hydrogen is produced onsite with an electrolyser. Clean energy powers the electricity-intensive process.

### Liquid $H_2$ produced at airport:

Gaseous hydrogen is converted to liquid by the liquefaction plant and is pumped into cryogenic storage tanks.



## Liquid hydrogen is brought to the airport apron via cryogenic pipelines, mobile refuelling bowsers or trucks with $LH_2$ tanks

### Hydrant system:

Liquid hydrogen is pumped from the storage tank through underground cryogenic pipelines to the apron.

### Hydrant system:

Autonomous hydrant dispenser vehicles provide a connection between the aircraft and the pipeline. An automated refuelling arm connects fuel hoses to the aircraft. The refuelling process is supervised remotely.

### Mobile bowsers:

Liquid hydrogen is pumped to a bowser loading facility. Robotic arms connect refuelling hoses to a bowser and pump liquid hydrogen into its tank.

### Mobile bowsers:

One or more refuelling bowsers travel across the apron to fuel the aircraft. After refuelling, the bowser travels back to the loading facility. The refuelling process is supervised remotely.

### Modular tanks:

Aircraft are refuelled using modular tanks which are loaded into aircraft with existing cargo handling equipment and replaced when empty.

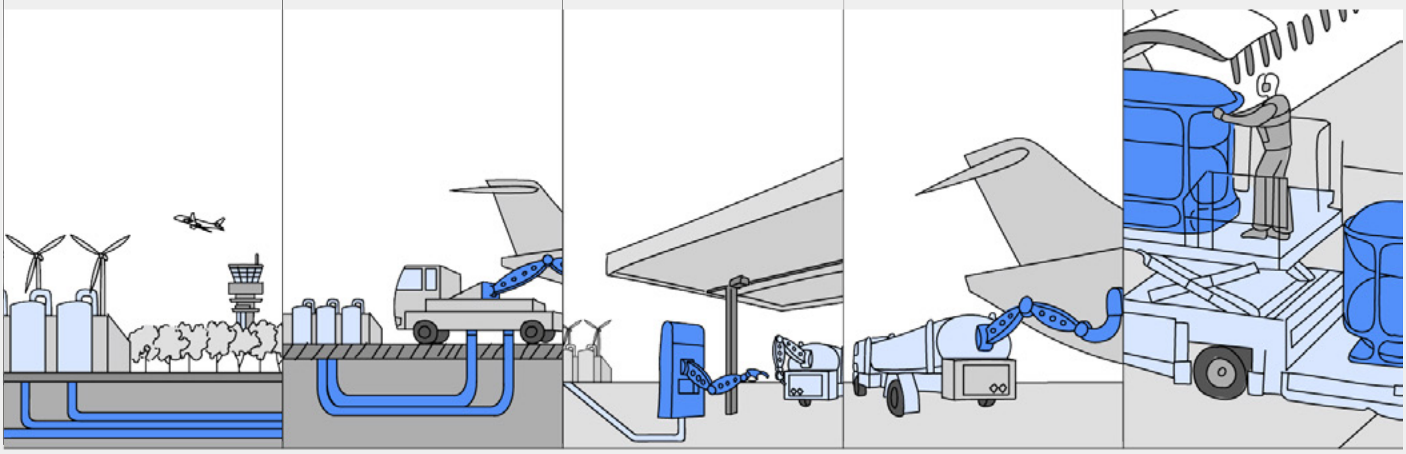
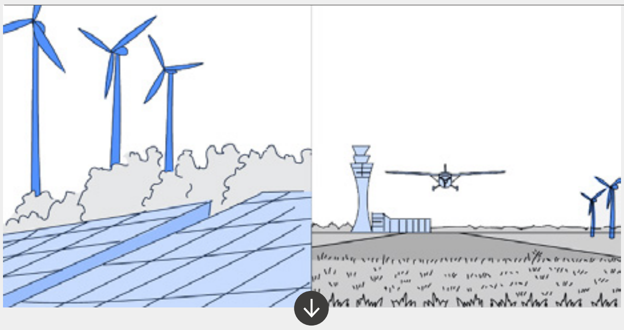
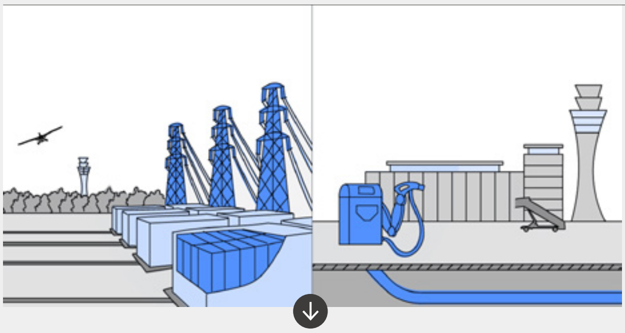


FIGURE 8 | A day in the life of battery-electric airport infrastructure



### Airports acquire clean energy from onsite or offsite production to power charging stations for battery-electric aircraft

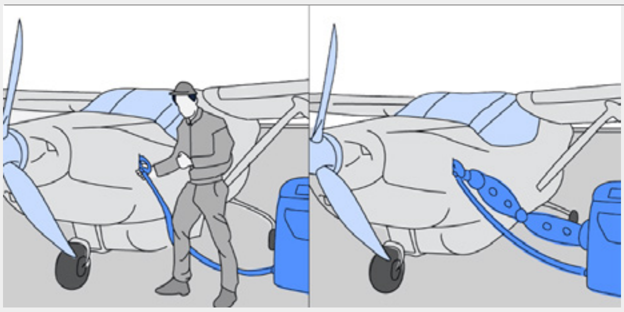
Clean energy is generated offsite by the airport's energy provider or it is generated on the airport site to supplement grid electricity. Energy supply is fed into high-capacity power lines.



### The electricity is transported to aircraft charging stations located at the ramp

Power lines feed energy into transformers. The airport's energy management system directs the supply of electricity from either the energy storage system or directly from the transformer into the power distribution network.

The power distribution network supplies electricity from the grid or through energy storage systems via underground cables to fixed aircraft chargers located at each gate serviced by battery-electric aircraft.



### Aircraft batteries are charged as needed ahead of flight

At the gate, aircraft are either automatically or manually connected to the fixed charging stations. If manual, this process is performed by a ground support employee with minimal additional safety equipment required. When batteries are sufficiently charged, aircraft are disconnected from the stations.

# 2 Investment to fund alternative propulsion infrastructure

Airports will need to begin planning for investments now to prepare for the arrival of the first alternative propulsion aircraft.

Delivering the necessary on-airport and off-airport infrastructure is going to require significant investment from airports and other stakeholders.

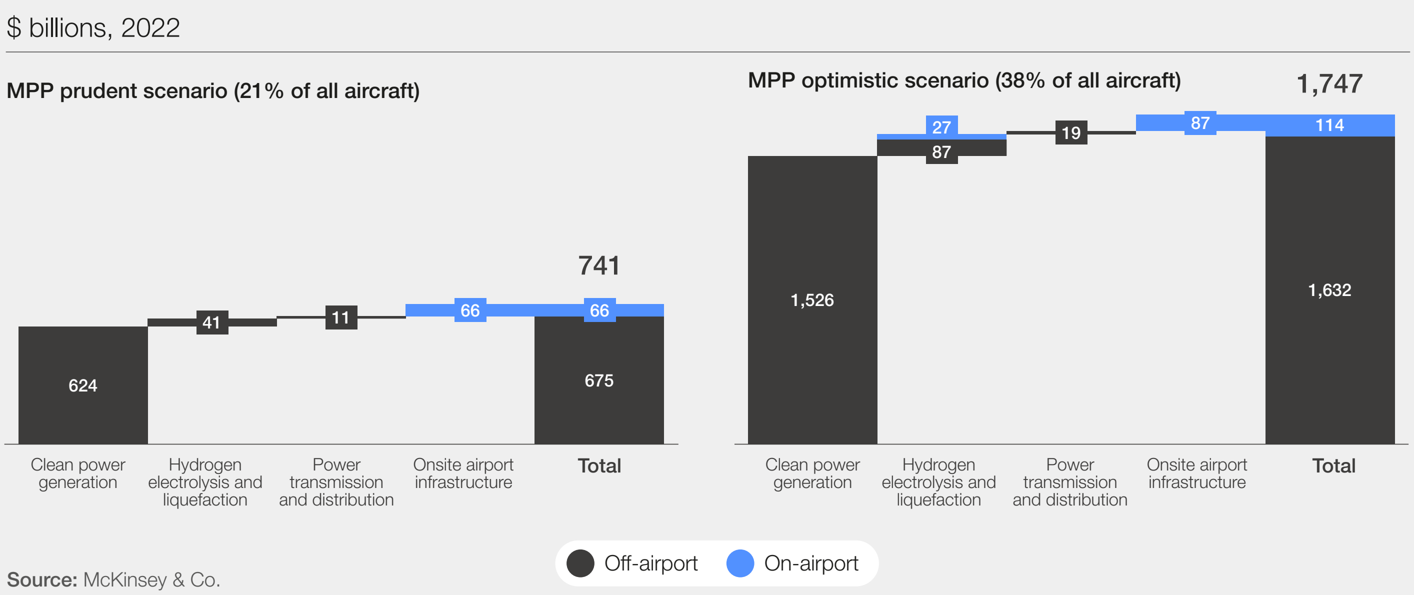
This section identifies the levels of investments that will be required for different types of airports and when these will need to be made.

## 2.1 Investment levels to support alternative propulsion

Based on the energy requirements for alternative propulsion identified in Chapter 1, it is estimated that the capital investment to deliver this will be in the region of $700 billion to $1.7 trillion in total for the period to 2050. As it is expected that about 90% of the energy consumption for alternative propulsion will occur off-airport, a similar proportion of investment will be for off-airport infrastructure including include clean power generation and distribution, hydrogen electrolysis and liquefaction, and power transmission and distribution.

**Insight 5:**
Shifting to alternative propulsion will require a capital investment of $700 billion to $1.7 trillion across the value chain by 2050. Approximately 90% of this investment will be for off-airport infrastructure, primarily power generation and hydrogen electrolysis and liquefaction.

FIGURE 9 **Total global capital investment required by 2050 to support alternative propulsion**

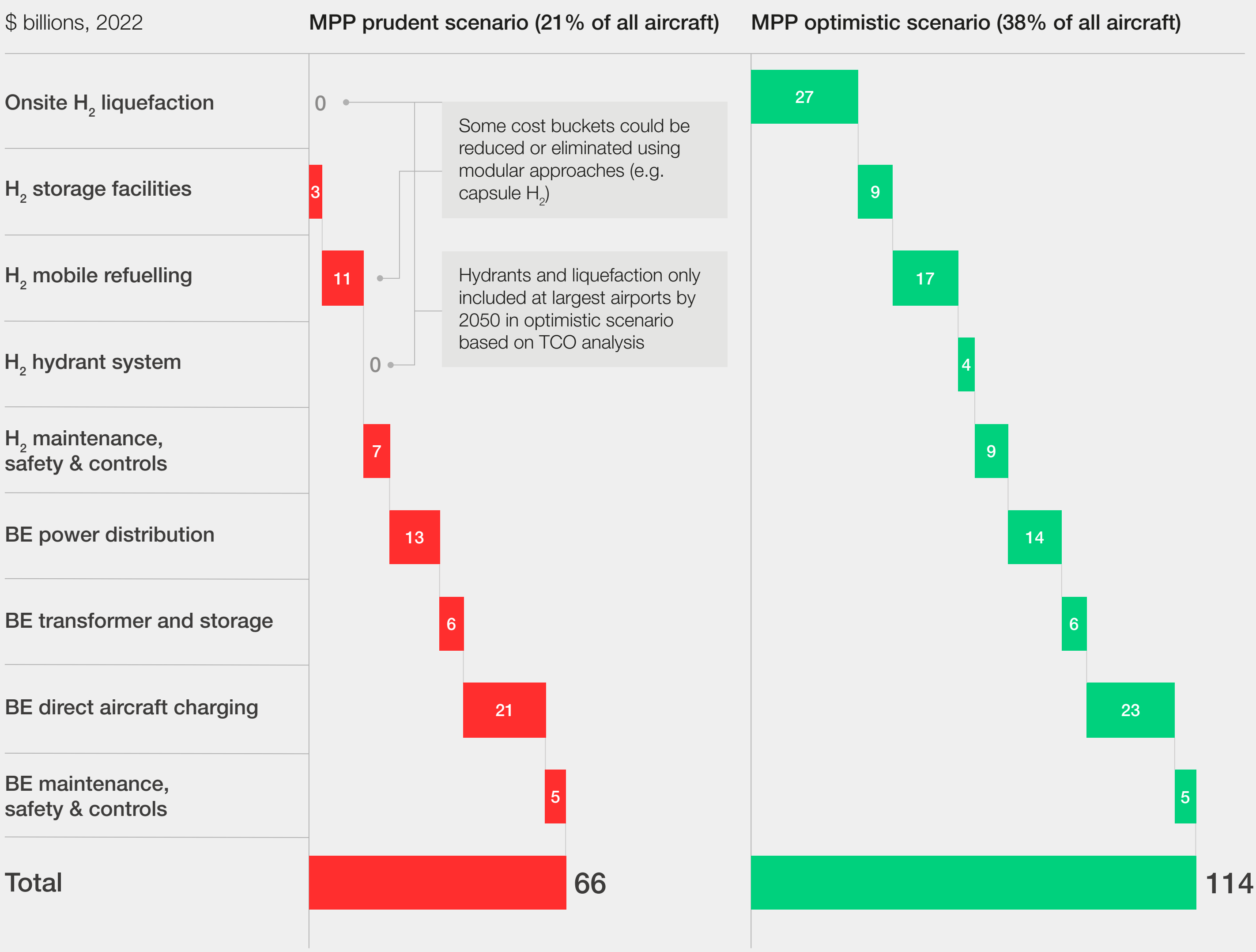



**Source:** McKinsey & Co.

Capital expenditures (capex) in green power generation for aviation alone would double current projections for global airport capex ($1.68 trillion by 2040 at $84 billion per year).[17] This makes it almost certain that aviation will need to partner with other industries (e.g. energy providers, hydrogen-consuming industries) to ensure the required investment.

On-airport infrastructure capex, which makes up the remaining 10% of total capex, is a more modest $66-114 billion in total up to 2050 (see Figure 10). This represents the equivalent of 0.8 to 1.4 years of incremental investment in airport reconstruction and expansion based on the current average spend.

FIGURE 10 **Global capital investment required by 2050 for on-airport infrastructure to support alternative propulsion**




**Source:** McKinsey & Co.

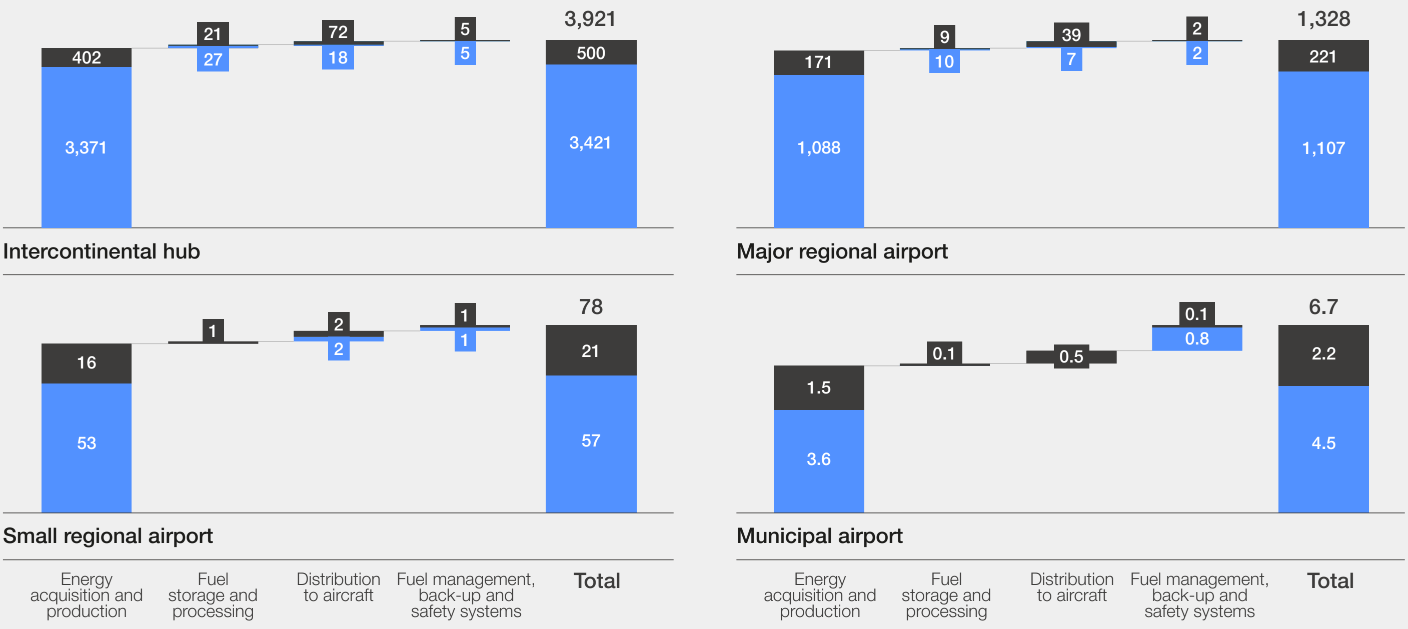
When the total on-airport capex required is broken down by airport archetypes, an intercontinental hub could expect to invest a total of approximately $3.9 billion up to 2050 across the whole value chain (including energy acquisition and hydrogen production) while the investment for a major regional airport would be in the range of $1.3 billion (see Figure 11).

Putting this in perspective, the capex costs for an international hub or major regional airport would be roughly equivalent to the LaGuardia Airport terminal expansion[18] or about 20% of the cost of London Heathrow's third runway project.[19] The costs for smaller airports will be much lower as these will not have to support larger aircraft that require more advanced infrastructure.

**Insight 6:**
Investment needed for airport infrastructure will be significantly higher for large airports than for smaller airports, but of similar magnitude to other major investments such as building a new terminal.

FIGURE 11 | **Total capex required for alternative propulsion infrastructure at different airport archetypes – up to 2050**

MPP prudent scenario ($ millions, 2022)




**Notes:** **1** Includes capex for zero-emission energy generation; **2** Airport would be unlikely to cover the full cost of energy acquisition and production on its own

**Source:** McKinsey & Co.

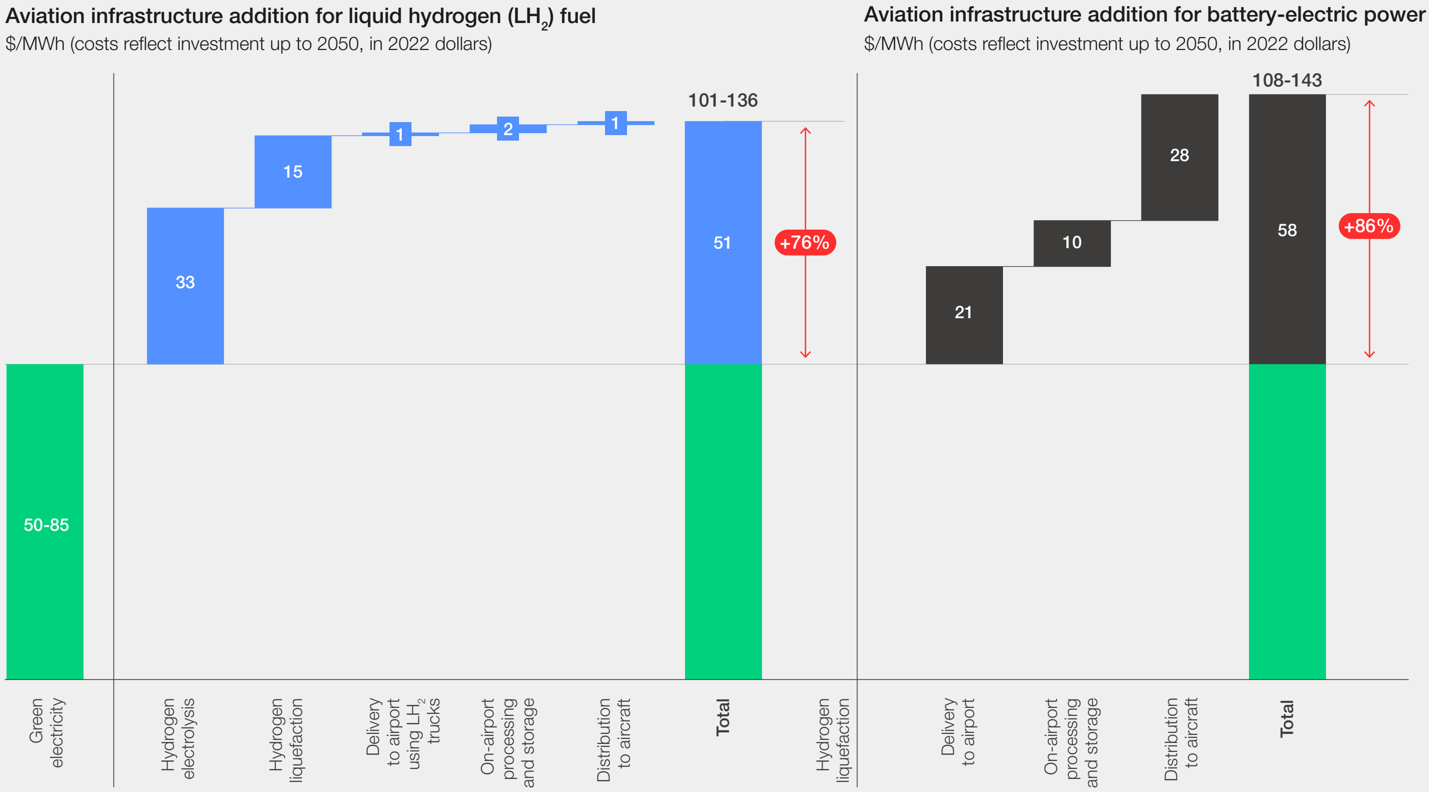
While this report focuses on the capital expenditure on infrastructure required for alternative propulsion, another important consideration for airports and operators that will determine the adoption of battery-electric and hydrogen aircraft is their operational expenditure – particularly the cost of energy to power them.

As well as the costs of producing green energy, there will be additional operating costs associated with the infrastructure needed to process the energy so that it can be used to power aircraft. This aviation infrastructure addition is analogous to the "crack spread" difference between a barrel of crude oil and the petroleum products refined from it.

Compared to the base-cost of green electricity, it is estimated that the aviation infrastructure addition for battery-electric aircraft – which covers the transmission of the electricity to the airport, its processing, storage and finally its distribution to aircraft - will be in the region of 86% in 2050. The total aviation infrastructure addition for hydrogen is expected to be lower – about 76%. This includes the costs associated with producing hydrogen via electrolysis, liquefaction, delivery, processing, storage and distribution to the aircraft.

**Insight 7:**
Costs to operators of alternative propulsion are expected to be around 76-86% over the market price for green electricity – reflecting additional aviation infrastructure operating costs.

FIGURE 12 | Aviation infrastructure additions for alternative propulsion in 2050




**Notes:**
Based on scenario involving a regional airport located 100 km from a large electrolysis and liquefaction facility in 2050 with $LH_2$ delivery to the airport by truck aircraft-fuelling using bowsers or other ground vehicles. Assumes green electricity prices of $50-$85 per MWh, corresponding to the midpoint of forecasts used in MPP's prudent and optimistic scenarios, respectively.

Costs account for upgrade of electrical transmission to an airport, but not for upgrade of electrical transmission to an offsite electrolysis and liquefaction plant. Hydrogen production assumes 69% electrolysis energy efficiency using green electricity at a 90% utilization rate, with straight-line depreciation of capex investments over a 25-year lifetime of assets. No inclusion of margins.

**Source:** McKinsey & Co.

## 2.2 Airport investment timelines for alternative propulsion

The levels of on-airport infrastructure investment required to support alternative propulsion are significant but likely to be manageable for airports in the context of overall investment. Furthermore, the number of battery and hydrogen-powered aircraft will enter service gradually, so it will be possible to ramp up infrastructure requirements at a similar pace. Nevertheless, airports will need to start investing now to support the first battery-electric and hydrogen aircraft flights, due to begin in just a few years.

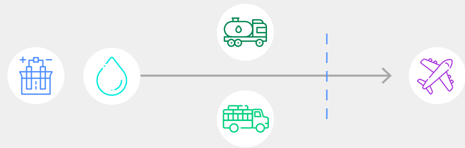
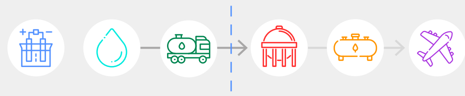
**Insight 8:**
The investments needed to meet 2050 goals must start now. The first elements of on-airport infrastructure must be in place by 2025 to meet expected energy demand.

Battery-electric aircraft infrastructure – including chargers, grid connections and energy storage systems – will be needed for at-scale battery-electric operations and could take between two and four years from investment to installation. Airports are already connected to power grids and may have electrical ground support equipment and EV-charging in place. While grid connection upgrades and energy storage systems are likely to be required as these aircraft become more popular, battery-electric infrastructure will be relatively easy to scale up.

By contrast, hydrogen infrastructure is much less likely to be incremental and airports may need to rebuild onsite hydrogen infrastructure as adoption increases – or they may be able to skip certain steps based on growth forecasts.

FIGURE 13 | **Models of liquid hydrogen ($LH_2$) distribution for aviation**

Increasing $H_2$ aviation traffic

| Model | Description | Illustration |
|---|---|---|
| 1 **All-in-one truck** | - Trucks deliver $LH_2$ fuel to the airport either in a single liquid tank or in modular capsules<br>- The same vehicles drive onto the ramp and refuel aircraft |  |
| 2 **Dedicated onsite bowsers** | - $LH_2$ tanker trucks deliver fuel to a storage facility at the airport<br>- $LH_2$ is distributed to aircraft on the ramp by dedicated bowsers |  |
| 3 **Hydrant system** | - $LH_2$ tanker trucks deliver fuel to a storage facility at the airport<br>- $LH_2$ is distributed to the ramp using underground pipelines, where aircraft are refuelled from hydrants |  |
| 4 **Onsite liquefaction** | - A gaseous hydrogen ($GH_2$) pipeline delivers fuel to the airport, where it is liquefied and stored<br>- $LH_2$ is distributed to the ramp via underground pipelines connected to hydrants and/or via capsules |  |

Electrolysis · Liquefaction · Capsule truck · $LH_2$ truck · $LH_2$ bowser · Processing & storage · Pipeline · Aircraft · Airport boundary

**Notes:** This list is not exhaustive. Other configurations may make sense depending on circumstance, e.g. onsite electrolysis and liquefaction at low traffic rates for isolated island airports.

**Source:** McKinsey & Co.

As noted in Chapter 1, there are multiple models for delivering hydrogen to an aircraft and these are explored in more detail in Figure 13. All of these are viable and the optimum solution for an individual airport will depend on the nature and extent of its hydrogen-powered aircraft operations. Early adopters will need to have all-in-one trucks ready by around 2025, when these aircraft first begin to appear. For the vast majority of airports – including major regional, small regional and general aviation airports – all-in-one trucks should be sufficient to meet the expected demand up until 2050.

In the case of some larger airports, dedicated onsite bowsers will also be a viable solution. At intercontinental hubs, a tipping-point will occur in the mid-2040s, making onsite liquefaction and hydrant systems more economically viable, based on flight volume forecasts.

These evolving requirements for hydrogen infrastructure will determine what investments are needed. Figure 14 displays the timelines and levels of investment that will be needed, depending on the airport type. Early investment in trucks to deliver hydrogen to aircraft will be $2-30 million, depending on the size of the airport. However, costs will increase to $670-960 million per year for intercontinental hubs in the event that they add onsite liquefaction and hydrant systems. It is assumed that there will be a five-year horizon for sourcing, investment and deployment of these systems, re-emphasizing the importance of airports beginning to think now about how to support limited hydrogen operations using all-in-one trucks.

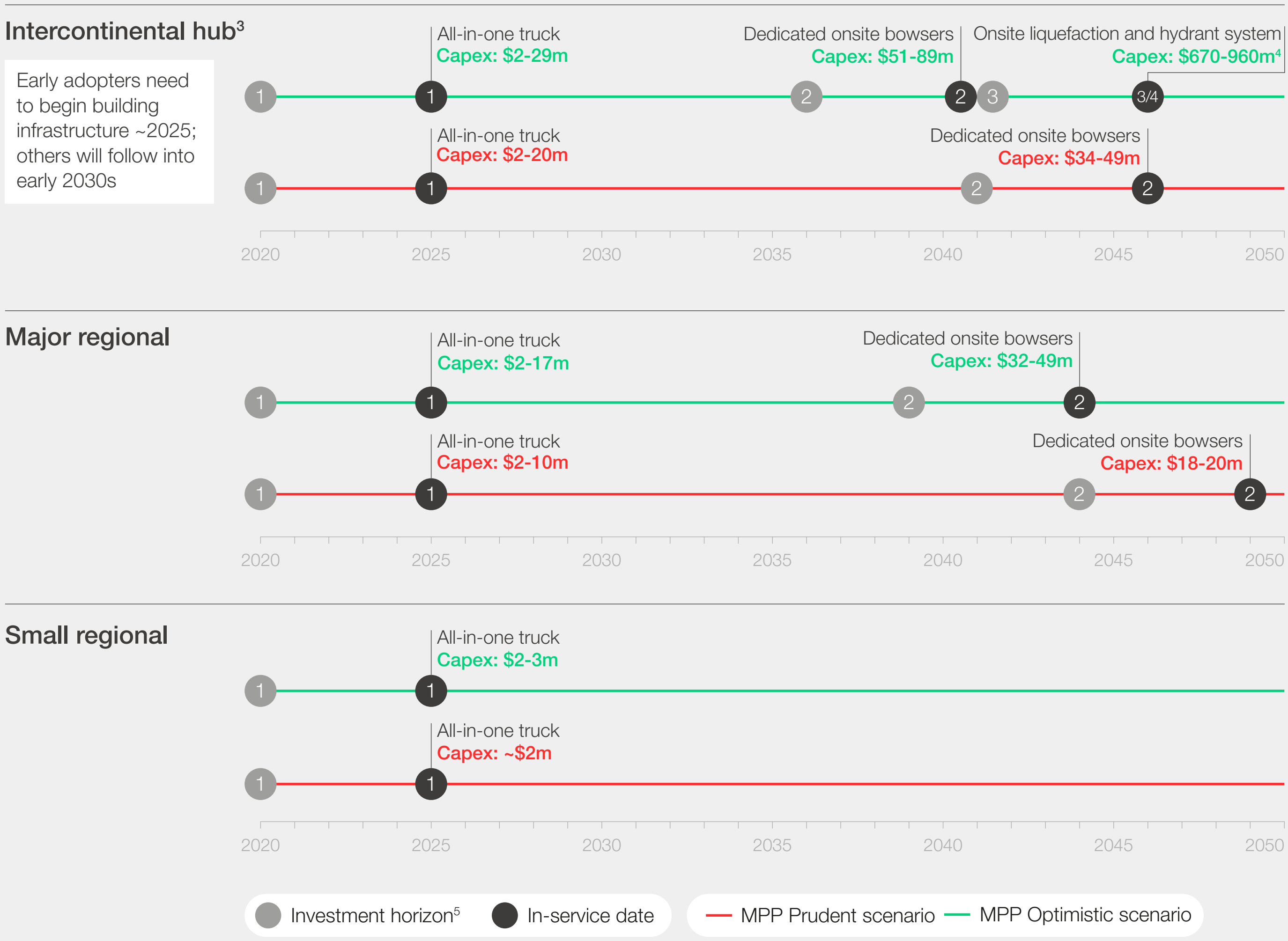
There will also be additional factors that affect the timing of hydrogen infrastructure expansion for different airports based on their unique circumstances. Some of the key items that airports will need to consider include:

– **Operational constraints**: Operational factors may have an impact on the timing of investments beyond the direct financial implications (e.g. switching to hydrants to avoid tarmac congestion).

- **Regional variation**: The adoption of alternative propulsion technologies is likely to vary significantly by region, especially in earlier years.
- **Access to hydrogen**: Airports further from large production facilities, ports or major pipelines may choose to expand storage and/or build pipelines to ensure consistent supply.
- **Operational simplification**: The widespread adoption of hydrogen capsules could eliminate the need for dedicated bowsers or hydrant systems, though this remains to be seen.
- **Geographic isolation**: For airports in remote locations, onsite production of hydrogen and/or tankering may be more operationally efficient than delivery from a hub.
- **Integration with other projects**: Airports may synchronize hydrogen investments with other capital projects (e.g. terminal expansion) to minimize disruptions to normal activities.
- **Leapfrogging**: Airports that anticipate rapid expansion in hydrogen adoption may choose to skip certain steps to avoid non-incremental investment (e.g. skipping delivery by truck and building a pipeline).

FIGURE 14 **Timelines and levels of airport investments in hydrogen infrastructure**

## Airport infrastructure requirements as a function of hydrogen aircraft adoption[1,2]




**Notes:**

**1** Other models (e.g. modular capsule hydrogen) could reduce infrastructure complexity; timeline based on average adoption rates of commercial and GA aircraft in the MPP scenarios.

**2** Capex is a function of the infrastructure models described in this document (e.g. all-in-one truck, dedicated onsite bowsers etc.) and does not include broader investments (e.g. electrolysis, battery charging, safety infrastructure etc.).

**3** Intercontinental hub assumed to be 10 km from hydrogen production facility; all other airports are assumed to be 100km from a hydrogen production facility.

**4** Includes $400-700 million in capex for the onsite liquefaction facility (cost per unit production assumed to be same as offsite).

**5** Investment horizon precedes in-service date by ~5 years, based on conversations with airport operators.

**Source:** McKinsey & Co.

# 3 Collaboration to deliver alternative propulsion infrastructure

Airports will need to work with their constituents and other green-industry users to deliver the infrastructure required for alternative propulsion.

The level of transformation required to transition to alternative propulsion and the level of investment needed mean airports will not be able to undertake this work in isolation. This chapter explores the need for collaboration both within the industry and with other industries.

## 3.1 Coordination within the aviation industry

When developing infrastructure for aviation, coordination will be required to ensure it can allow for battery-electric and hydrogen aircraft to operate at multiple airports simultaneously. To develop viable networks, it will be essential to ensure there is infrastructure in place at a sufficient number of airports. This will also allow for any rerouting that may be required, such as during diversions.

While large airports will bear the highest costs in the switch to alternative propulsion, initial use cases for alternative propulsion will likely be between smaller airports for battery-electric flights or on single point-to-point routes between large and mid-sized airports for aircraft powered by hydrogen. Coordination of investment at smaller airports within smaller geographic regions will therefore be necessary for the operation of battery-electric aircraft. For hydrogen-powered aircraft, coordination will be needed between large and small airports – possibly across multiple national jurisdictions – and therefore represents a bigger challenge.

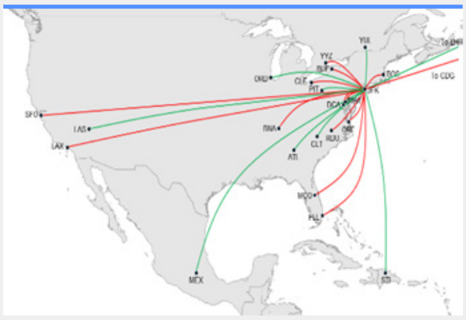
To understand the level of coordination that would be needed, under the scenarios modelled by MPP's Aviation Transition Strategy, hydrogen propulsion is projected to power 24-36% of Amsterdam Schiphol Airport's flights by 2050 – which equates to about 14-25 routes for a traditional hub. At Singapore's Changi Airport, it would be approximately 16-32% of flights, requiring 3-10 routes to activate a hub.

**Insight 9:**
To harness the power of network effects and regional connectivity, coordination of infrastructure investment will be required to make alternative propulsion operations feasible.

Examples of the coordinated investment that would be needed to achieve this already exist – for instance, the work being done by the Avinor company that operates most of the civil airports in Norway.[20] Replicating this coordination in other parts of the world will require airports, operators and other stakeholders to come together to catalyse action within and across regions.

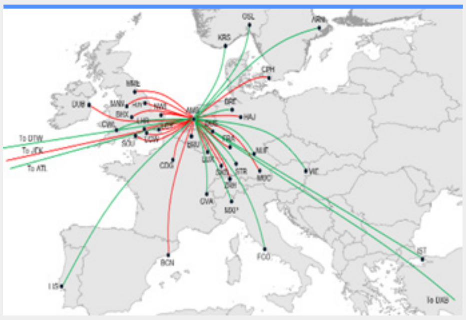
FIGURE 15 | **Potential hydrogen aviation network scenarios in 2050**

### New York JFK



- 21-36% alternative propulsion flights
- 21-42 routes to activate hub

### Schiphol Airport AMS



- 24-36% alternative propulsion flights
- 14-25 routes to activate hub

### Changi Airport SIN

- 16-32% alternative propulsion flights
- 3-10 routes to activate hub

### Implications for airports

MPP Prudent scenario | MPP Optimistic scenario

**Hubs will need a network of spokes** to operate effectively at scale by 2050

To achieve targeted adoption, **hub airports will depend on spoke airports installing their own alternative propulsion infrastructure**, to activate their route networks

**Infrastructure investment must be coordinated regionally** to maximize utilization and return on investment

**Note:** Activating a hub is shown as the number of routes required to meet the MPP's alternative propulsion targets for hydrogen and battery-electric aircraft (based on 2019 flight schedules). Examples of routes are for illustrative purposes only.
**Source:** McKinsey & Co.

## 3.2 Coordination with other industries

The imperative for airports and the aviation industry to collaborate beyond their traditional base of partners will prove as important as intra-industry coordination. Given the significant capex investment required (of which around 90% will be for off-airport infrastructure), airports will need to seek out partnerships across the infrastructure value chain to successfully ramp-up alternative propulsion.

**Insight 10:**
The aviation industry will need to partner with other industries to secure enough green electricity and hydrogen in a supply-constrained environment and to have a voice in shaping the future of the hydrogen ecosystem.

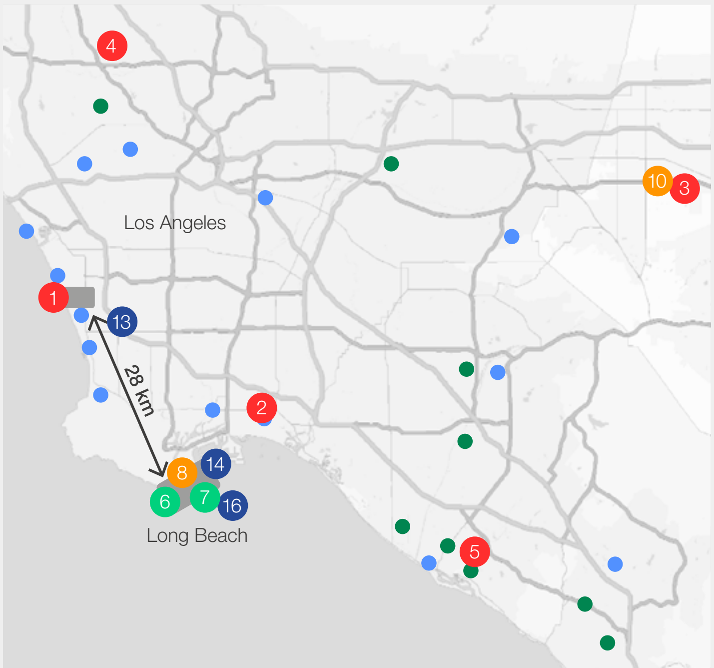
Airports could do this by exploring partnerships with green energy suppliers for electricity generation and hydrogen production. They could also potentially link up with high-demand hydrogen consumers (e.g. refineries, steel or fertilizer manufacturers), as well as sustainable aviation fuel producers (some of which already consume hydrogen as a feedstock) that could vertically integrate to provide direct-fuel hydrogen to airports. This approach would not only secure sufficient green energy and hydrogen production to meet airport hydrogen demand during the ramp-up of alternative propulsion technology, it would also enable airports to invest in the development of efficient electrolysis and liquefaction technology, with the goal of reducing cost and/or bringing production closer to the airport.

For energy storage, processing and management, airports could partner with equipment manufacturers (e.g. for battery charging, hydrogen storage and handling) and clean hydrogen and ammonia fuel handlers in other transport industries, such as high-volume trucking and shipping. Through these partnerships, airports could accelerate and influence the design of airport-specific infrastructure, as well as establish hydrogen-specific fuel consortiums to share the risk and cost of fuel storage and distribution, similar to those that currently operate for jet fuel.

For distributing energy to aircraft, partnerships with aircraft OEMs, operators and safety regulators could help airports to understand and influence the development of infrastructure for aircraft charging and fuelling, along with the associated ground equipment. Such partnerships could also help airports understand the safety requirements for the operation of alternative propulsion aircraft, in turn informing investment and operational planning decisions.

To help with this work, airports can begin to map the local ecosystem of hydrogen and energy projects to identify specific partners. Figure 16 provides an overview of what this analysis could look like for the city of Los Angeles.

FIGURE 16 **Case study: Los Angeles – hydrogen ecosystem layout**




### Outside of map area

| 9 | 11 | 12 | 15 |
|---|---|---|---|
| Palm Springs (~100 km) | Fresno (~300 km) | Bakersfield (~230 km) | Utah (~700 km) |

*Not exhaustive*

The area of **Greater Los Angeles** is home to multiple $H_2$ initiatives and an ambitious project from **SoCalGas** to provide **access to $H_2$ through the gas pipeline network**, channeling in 10-20 GW of electrolysis capacity in the future.

### Commercial airports

1. Los Angeles International Airport (LAX)
2. Long Beach
3. Ontario
4. Hollywood Burbank
5. John Wayne

### Port facilities

6. Port of LA
7. Long Beach Port

### $H_2$ distribution

- Hydrogen fuelling stations (supplied by $GH_2$ delivery) (blue)
- Hydrogen fuelling stations (supplied by $LH_2$ delivery) (green)

### Upstream $H_2$ projects

8. Toyota Tri-Gen
9. 2.5 MW Hydrogenics electrolyser project
10. Linde Green $H_2$ production
11. 120 MW Plug Power electrolyser project
12. 75 MW Fusion Fuel project

### Industrial $H_2$ users

13. Universal Hydrogen (airplane refitting)
14. Heavy Duty Truck demonstration
15. Intermountain Power Project ($H_2$ electricity production)
16. FC marine vessel demonstrator

**Source:** McKinsey & Co., Hydrogen Fuel Cell Partnership, Station Map.

# Conclusion

## Alternative propulsion presents airports with an opportunity to position themselves at the heart of the transition to sustainable aviation.

The introduction and growth of alternative propulsion within the aviation system will require significant changes to current industry value chains, necessitating huge investments in clean energy production, onsite investments in airport infrastructure and collaboration across multiple stakeholders – both within and outside the traditional aviation sector.

While the first of these changes will appear on the horizon sooner than some may realize, they present opportunities as well as challenges to airports and the wider sector. The changes resulting from alternative propulsion, while significant, will also be gradual – allowing airports and their constituents to prepare accordingly. To ensure airports are ready for the changes they will face, they can begin by taking the following priority actions:

**Assess how alternative propulsion will impact airport operations**

- When will demand for alternative propulsion aviation arrive at my airport?
- What type(s) of aircraft will I need to accommodate?
- What is the detailed business case for alternative propulsion at our airport?

**Identify natural partners in the green energy ecosystem**

- Where can I best acquire green energy?
- Who can supply it?
- Which hydrogen-consuming industries near my airport should I partner with to signal demand to suppliers?
- Who are the broader set of stakeholders with whom I share an interest?

**Incorporate alternative propulsion infrastructure into investment and operational planning**

- When do I need to start investing in the energy infrastructure necessary to meet my future needs?
- What type(s) of on-airport infrastructure will best meet my anticipated future needs and how will my operations change?

**Engage regulators to understand and help define future safety requirements**

- What will be the safety requirements for operating and refuelling battery-electric and hydrogen-powered aircraft?

While much work remains to understand the infrastructure and investment needs on an airport-by-airport basis, this shift represents a generational opportunity to build new, green businesses and define the future of aviation. Target True Zero stands ready to provide a platform for future discussions and to support key stakeholders in their efforts to deliver a sustainable aviation sector compatible with its 2050 net-zero goals.

# Appendix: Methodology and references

This report has been produced using insights developed by McKinsey & Company from workshops and discussions held by the World Economic Forum's Target True Zero Coalition with industry experts. Several foundational assumptions around energy consumption and investments were used to inform this work, as detailed in Figure 17.

FIGURE 17 **Key assumptions of energy consumption and investment model**

| | | Production efficiency<br>Average output as % of peak capacity | Capex required<br>$ per kW or kWe in 2050 (2020 dollars) |
|---|---|---|---|
| Zero-emissions electricity generation | Solar photovoltaic | 18% | $297 |
| | Wind – onshore | 30% | $867 |
| | Hydro – reservoir | 50% | $2,476 |
| | Nuclear | 92% | $4,385 |
| Green hydrogen production (electrolysis) | Small-scale (120 TPD) | 69% | $358 |
| | Large-scale (5,000 TPD) | 69% | $221 |

**Note:** TPD – metric tonnes per day

**Source:** McKinsey & Co.

*Not exhaustive*

Other key assumptions used to develop this report include the following:

– Technical improvements in liquid hydrogen handling are assumed to reduce end-to-end losses to <5% in most cases by 2050.

– Hydrogen electrolysers are assumed to be 69% efficient in 2050, with a capex of $221-358 per kWe.

– A 3% p.a. decrease in the cost of liquid hydrogen storage and transportation tanks is assumed as liquid hydrogen technology scales, based on expert interviews.

– The assumption that the primary energy for alternative propulsion aircraft will be generated entirely by renewable and/or zero-emission technologies with a 35/35/20/10 mix of solar, wind, hydro and nuclear, respectively.

– Turnaround times for hydrogen and battery-electric aircraft are assumed to be nearly the same as current aircraft, once technology matures and refuelling/recharging procedures become routine by 2050.

– Airports are assumed to be located 100 km from the nearest major hydrogen production facility.

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The analysis was built on a range of additional foundational assumptions from a variety of other reports and references listed below:


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# Endnotes


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3. Alternative propulsion technologies include hydrogen, battery-electric and hybrid-electric powertrains. These technologies are distinct from sustainable aviation fuel (SAF), which is an alternative fuel, but not a form of alternative propulsion as the propulsion technology itself (the aircraft engine) does not change.
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5. Full life-cycle emissions of battery-electric aircraft will depend on the source of the electricity used to charge them. Use of fully renewable energy would reduce these impacts to close to zero, but if electricity is produced from non-renewable sources in some instances impacts could be greater than those of burning jet fuel. Other sources of climate-warming emissions from battery-electric aircraft include those associated with the manufacture of the batteries themselves.
6. As with battery-electric aircraft the full life-cycle impact of hydrogen-powered aircraft will depend on the methods used for producing hydrogen.
7. Condensation trails – or contrails – are created under certain conditions from condensed water vapour released at altitude which forms droplets or crystals around an aerosol particle, such as the soot emitted by burning jet fuel. As contrails are released high up in the atmosphere, they can form clouds that prevent heat from leaving the Earth. It is believed that contrails could at least double the total climate warming impact of aviation compared to the effect of aircraft's $CO_2$ emissions alone – although there remains significant scientific uncertainty about their overall impact.
   There is even greater uncertainty when it comes to the impacts of contrails from hydrogen-powered aircraft due to their different composition. For hydrogen fuel cell powered aircraft, if water were to remain as a vapour, hydrogen contrails could form; however, if that water by-product were managed and condensed into liquid form, it may be possible to eliminate these impacts entirely. For hydrogen combustion aircraft, contrails would be more likely to form due to increased water vapour, but it is not known whether their different composition would have a greater or lesser impact than contrails from jet fuel or SAF. Even if the impacts of hydrogen contrails were greater than those produced from flying on jet fuel, there remains the possibility that changes to aircraft operations (such as flying at certain altitudes) could be used to reduce or eliminate contrail formation from both hydrogen and traditional jet fuel aircraft – though with the latter this may impose a carbon penalty from flying less direct routes.
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