LOGISTICS AND MARKET PREFEASIBILTY STUDY

Hydrogen supply to Norwegian airports

Avinor AS

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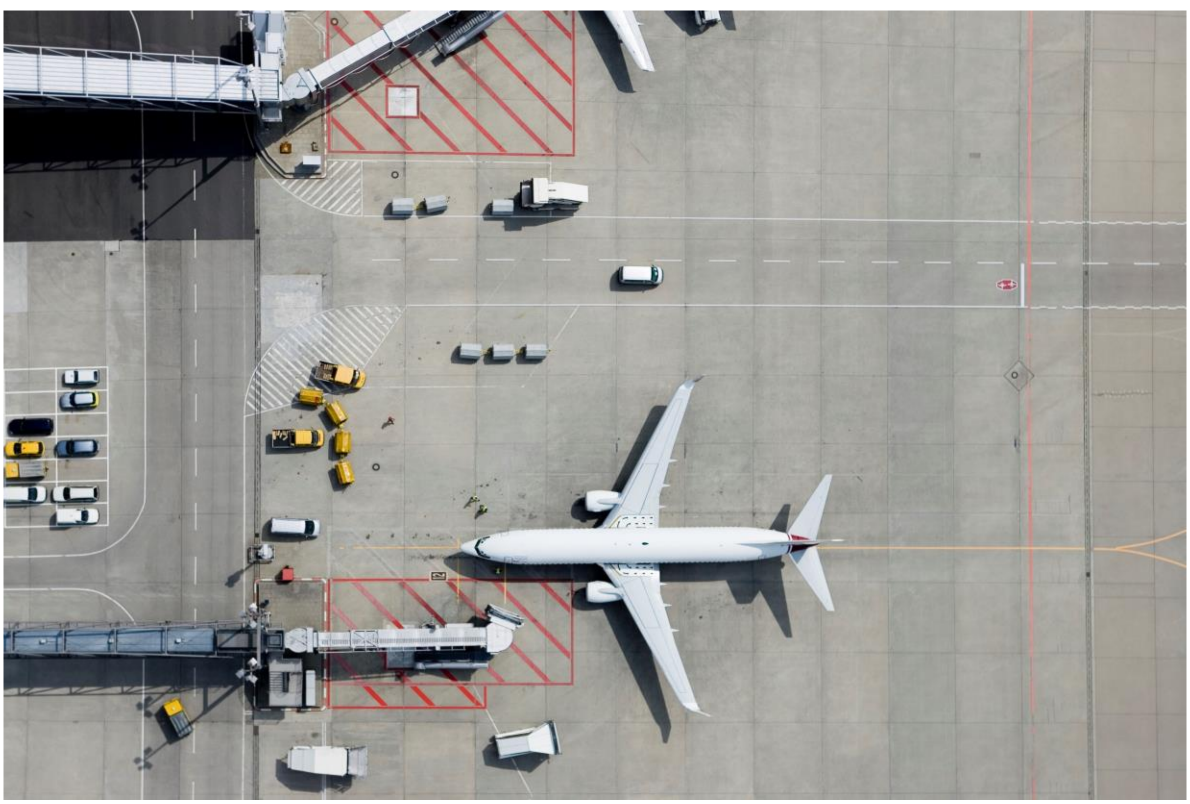

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Objective: The main purpose of this report has been to provide maps linking planned and existing hydrogen production and storage to Avinor's airports as a basis for future preparation of hydrogen supply to Norwegian airports. It thus aims to provide a brief overview of the current hydrogen landscape in Norway based on existing and public knowledge, connect possible hydrogen production and distribution projects to Avinor's airports as potential suppliers, and introduce value chain concepts and ideas around how the technology could play a vital role in decarbonising the Norwegian aviation industry.

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1 INTRODUCTION

The amount of documentation and reports on civil aviation and hydrogen is growing. **The main purpose of this report has been to provide maps linking planned and existing hydrogen production and storage to Avinor's airports as a basis for future preparation of hydrogen supply to Norwegian airports.** It thus aims to provide a brief overview of the current hydrogen landscape in Norway based on existing and public knowledge, connect possible hydrogen production and distribution projects to Avinor's airports as potential suppliers. Furthermore, the report briefly introduces value chain concepts and ideas around how the technology could play a vital role in decarbonising the Norwegian aviation industry. Note that this is a high-level study and a snapshot of the situation based on input from existing reports, observations and public announcements, and does not include all project details. Feasibility studies for projects are evolving, and may change location, size and timeline.

Hydrogen is widely recognised as an important facilitating energy carrier to enable the energy transition, and particularly in decarbonising hard-to-abate sectors of the economy, such as industry and transportation. The production of renewable (or "green") hydrogen is currently reasonably far off reaching cost-parity with hydrogen produced from natural gas. However, several countries have recently released strategies setting targets and committing resources to bring the cost *and* emission intensity of production down. For example, the EU is taking a leading position in establishing a market for hydrogen and recently released its EU Hydrogen Strategy, which sets out ambitious targets for renewable hydrogen production (10 million tonnes annually) and electrolysers (40 GW) by 2030. Additionally, several EU countries, for example Germany, Sweden and Denmark have recently released hydrogen strategies. Norway issued its own strategy in 2020, with updates in 2021 and 2022, which sets out priorities with regards to hydrogen technology development, research and policy.

This recent activity all points to hydrogen increasingly being recognised as important part of a future decarbonised economy and that policy makers, industry representatives and other stakeholders are positioning for strategic roles in the emerging hydrogen value chain.

The use of hydrogen in aviation is still in its infancy, but it is increasingly seen as a viable option for decarbonising the sector. Hydrogen is a useful energy carrier, and can help to reduce greenhouse gas emissions from aviation in several ways:

- In connection with the production of biofuel (hydrogenation)
- As an input factor in the production of e-fuels
- By direct combustion in custom jet engines
- In a system with fuel cells and electric motors

Furthermore, in the future, hydrogen may play an important role at airports, for example in backup power applications, or as an energy carrier in heavier vehicles (Avinor, 2020).

Fuel cell electric aircraft driven by compressed hydrogen can have longer ranges than battery electric aircraft with today's technology. For longer ranges liquid hydrogen or other zero emission fuels would be needed (ACI, ATI, 2021). Several initiatives are currently underway to test and prove the viability of hydrogen powered aircraft, perhaps most notably Airbus' endeavour to introduce a commercial zero-emissions aircraft powered by hydrogen by 2035 (Airbus, 2022).

Avinor started early to test hydrogen concepts. During autumn 2014 airport patrol at Avinor Oslo Airport (OSL) started using a Hyundai Fuel Cell Electric Vehicle (FCEV). In October 2015 Prime minister Erna Solberg opened a hydrogen fueling station at OSL. It was located landside and was thus also available for the general public. The fueling station was owned and operated by the company HYOP on land leased for free from OSL. However, due to the rapid market uptake of battery electric cars compared to FCEVs in the light duty segment, the fueling station went out of operation in late 2018 and Avinor sold the hydrogen car in 2019.

Avinor sees a strong potential for hydrogen in aviation and believes that Norway in many ways is ideally positioned to lead the way in the development of the sector. For example, Norway has significant potential for large-scale production of both low carbon (blue) and zero carbon (green) hydrogen. Norway’s gas reserves, large share of renewable electricity production, low electricity prices, large areas suitable for offshore wind, and proximity to UK and EU markets, translate to the potential for a strong market position in a future hydrogen market. Norway also has a relatively large share of smaller, regional airports that are well-positioned to be early movers in introducing hydrogen to the aviation value chain.

2 PRODUCTION OF HYDROGEN

Hydrogen is produced all over the world today, about 115 million tonnes per year. In Europe more than 450 hydrogen production sites are in operation with a total production capacity of around 10 million tonnes hydrogen per year and emitting >80 million tonnes CO_2. Figure 2-1 shows hydrogen production sites, divided into by-product, captive and merchant facilities. 92% of all current hydrogen production plants in Europe use fossil fuels as feedstock, mostly natural gas, while the rest use grid power which is mainly fossil based power production.

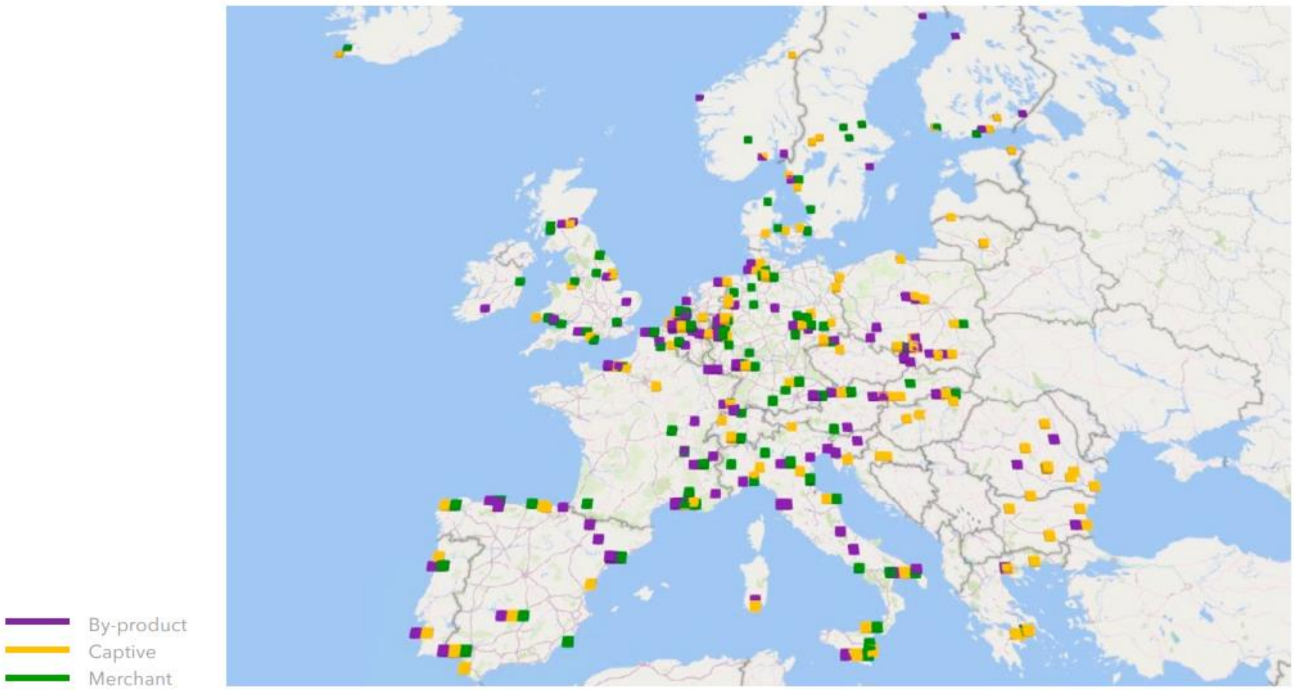


Figure 2-1: Hydrogen production in 2020 (Hydrogen Europe, 2020)

The carbon intensity of hydrogen production has become an increasingly important component for differentiating hydrogen production sources. These descriptions are generally undertaken with color coding, of which the most frequently used colors are grey, blue and green. More recent terms for the two latter are low-carbon and renewable hydrogen. Grey hydrogen is defined as hydrogen derived from steam methane reformation (SMR) without carbon capture and storage (CCS). Blue hydrogen is low-carbon and is mainly SMR with CCS, but can also be hydrogen derived from other fossil fuels with CCS. Green or renewable hydrogen, on the other hand, is produced with renewable energy, for example through electrolysis of water using renewable electricity or reformation of biogas.

There are, however, a range of additional color codes for hydrogen production, see figure below. These reflect:

a. The various fossil fuel feedstocks hydrogen can be derived from

b. The hydrogen production technologies applied

c. The energy used to fuel the hydrogen production process.

Combinations of feedstock, technology and energy has led to a wide specter of environmental characteristics and can have ranges of CO2 footprint from >10 to less than 1 kg CO2 per kg H2 for the hydrogen production value chains. These colors, which are reflected in Figure 2-2, are not the result of an internationally accepted taxonomy and should be considered an informal way to define the variety of environmental characteristics for hydrogen. To reduce this classification ambiguity, a key focus of the ongoing discussions in industry forums and actors in the emerging hydrogen economy is to establish clear classification of hydrogen. This necessitates defining metrics to measure the environmental impact of hydrogen, and thus by extension its origin.

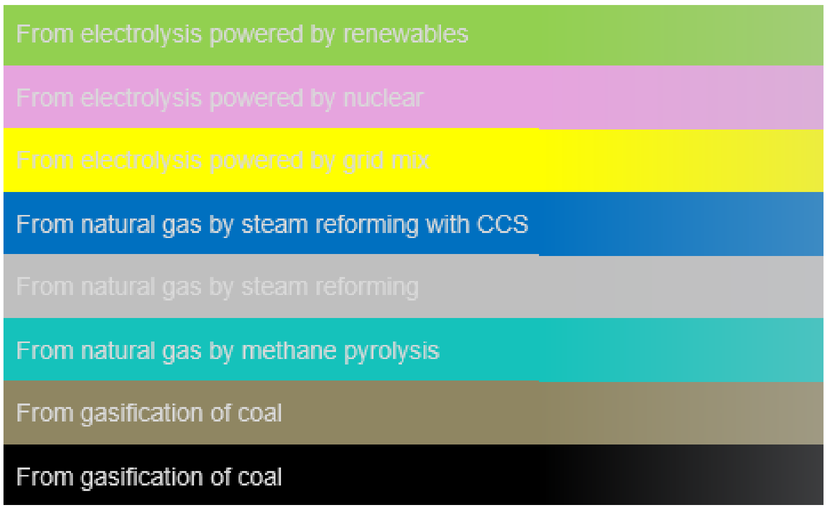


Figure 2-2: Hydrogen colour palette (DNV)

The EU Taxonomy, in this regard, has set the direction of travel by setting a threshold of carbon intensity to determine to whether a unit of hydrogen can be considered sustainable or not. As such, rather than a color palette for hydrogen, the future classification is likely to be whether hydrogen is renewable or low-carbon, or not. The EU Taxonomy is the EU's own classification system to determine whether economic activities are in line with EU sustainability targets. The most notable of which are to reduce emissions by 55% from 1990 levels by 2030 and achieving carbon neutrality by 2050, which in turn dictates the technical screening criteria (TSC) for 'the manufacturing of hydrogen' economic activity.

To align with the TSC for climate mitigation, hydrogen will have to be below a threshold of 3kg of CO_2 per kg of hydrogen produced (European Commission, 2021). Similarly, the threshold is 4,9 in China, and in the US a value of less than 6 will give tax credits, where 0,45 $kgCO_2/kgH_2$ will give up to 3 USD/kg in tax credits. These thresholds may be tightened at least every five years, reflecting tightening carbon budgets and technological development of hydrogen production. Crucially, the Taxonomy is agnostic on the use of technology, feedstock and energy source, as long as the carbon intensity target can be met. Over time, tightening carbon intensity requirements will exclude certain forms of hydrogen production.

2.1 Renewable green hydrogen - How?

2.1.1 Electrolysis technologies

Green hydrogen is produced with renewable energy, mainly through electrolysis that uses 100% renewable electricity but also through biogas reformation. Electrolysis splits water (H_2O) into hydrogen (H_2) and oxygen (O_2) by applying an electric current, and the carbon footprint of the electricity consumed dictates whether the hydrogen produced is green or low carbon

(DNV, 2021a). The reformation of biogas, on the other hand, uses various carbon capture technologies with a renewable gas feedstock.

The main goal of hydrogen production technology development is to reduce the levelized cost of hydrogen (LCOH). For this, the main levers are the electricity consumption and investment cost, as well stack degradation timeframe. There are, at present, four main electrolysis technologies; Alkaline Electrolysis (AE), which has been widely used for ammonia and fertiliser production over the 20th century and is the most mature electrolysis technology, Proton Exchange Membrane (PEM), which is characterized by the use of a solid electrolyte, a quick response time and will typically be pressurised, Solid Oxide Electrolysis (SOE), which is characterised by high operating temperatures, high efficiency and using steam instead of water, and Anion Exchange Membrane (AEM), which is similar to PEM and is the least developed technology. AE currently is the cheapest technology, but PEM is taking large steps towards maturity A more thorough introduction to electrolysis technologies is provided in DNVs *Technology Progress Report* (DNV, 2021b).

2.1.2 The uphill battle facing green hydrogen

Green hydrogen production was first performed at an industry scale in Norway 100 years ago, and lasted until natural gas hydrogen production took over. Renewable hydrogen has now a comparatively high cost, when compared to alternatives with higher carbon intensity. On the one hand, strategies such as the EU or German hydrogen strategy have an overarching focus on green hydrogen. On the other hand, the EU taxonomy requirements reflects an awareness that an initial ramp up in hydrogen production in Europe will need to tap into production with higher carbon intensities, as these still register a lower cost. DNV expects cost parity between green and other colors of hydrogen production to take at least a decade. Figure 2-3 highlights that cost parity for electrolysis-based green hydrogen production is only expected post-2030, while blue hydrogen production capacity deployment will start ramping up from the mid-2020s.

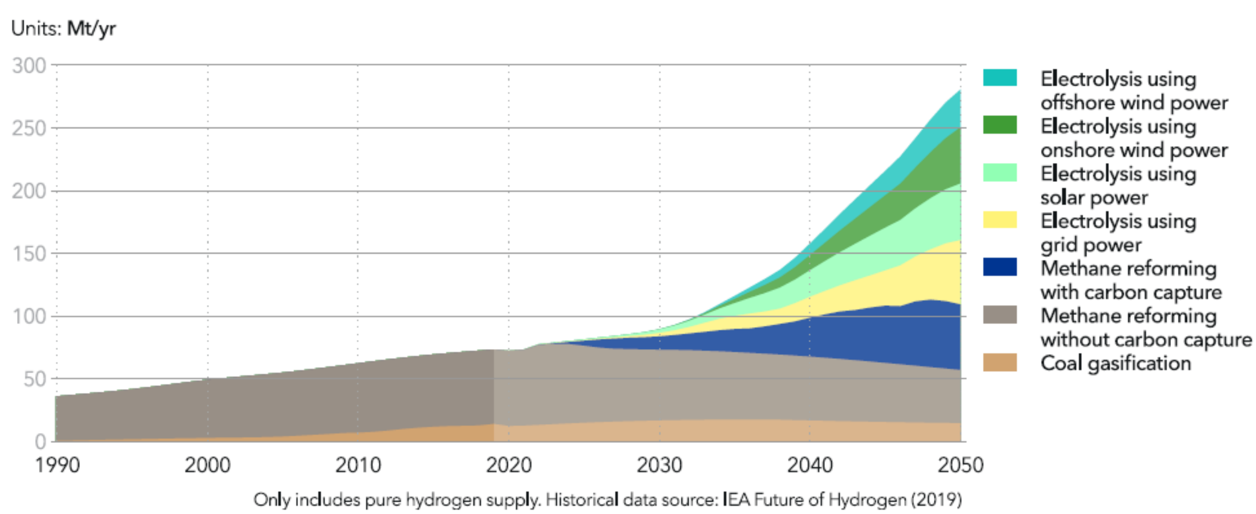


Figure 2-3: World hydrogen production by source (DNV, 2021c)

Ramping up green hydrogen production is contingent on further cost reductions for electrolysis technology and renewable electricity generation, combined with policy support that facilitates such reductions and increases the cost of emitting for other hydrogen production alternatives.

- **Cost of carbon emissions:** In Europe, the cost of emitting carbon increased significantly over 2021, with the EU ETS price trebling over the year from EUR30/ton to over EUR90/ton, in part reflecting a tightening regulation under the ETS phase IV and an expectation for additional tightening under 'Fit-for-55' and the ramp up in fossil fuel energy production.
- **Electricity costs:** The European power market is at the time of writing (January 2022) registering record-highs for electricity prices. Cost-competitive green electricity is a prerequisite for the rollout of green hydrogen, and electrolysis has been touted as a potential large source of electricity demand that can absorb peak renewable generation at low costs. To roll-out green hydrogen production, the EU will need to ramp up renewable capacity deployment substantially. Given that electrification is a key decarbonization driver in transport, buildings and to some extent industry, growing the volumes of renewable energy enough to feed direct electrification and green hydrogen (indirect electrification through electrolysis) is essential.
- **Capacity targets and support:** A number of EU markets have concrete green hydrogen capacity targets, and the EU has set a green hydrogen production capacity target of 40GW by 2030. These targets are set to be accompanied by targeted support mechanisms that seek to bridge the cost-competitiveness gap between green hydrogen and other colors.

2.2 Low carbon blue hydrogen

While steadily increasing the ratio of green hydrogen is essential to deliver on net zero aspirations mid-century, there is consensus that low-carbon hydrogen is a prerequisite in the near-to-medium term. According to the DNV Energy Transition Outlook, blue hydrogen from SMR with CCS will be key to scaling the low carbon hydrogen economy before 2030 (DNV, 2021c). A key facet of this is that blue hydrogen can tap into existing natural gas value chains and proven SMR technology coupled with CCS to deliver feedstock, as a transitional solution until green hydrogen is sufficiently competitive and renewable energy capacity ramped up. In line with this, countries with large fossil fuel reserves, such as Norway, tend to lean towards formulating hydrogen strategies that leaves room for both green and low carbon blue hydrogen. Such strategies naturally also focus on facilitating the capture and storage of carbon, in Norway's case building on existing CCS capabilities.

In terms of carbon intensity, low carbon blue hydrogen can deliver substantial emission reductions compared to SMR without CCS and electrolysis from grid sourced power in markets with fossil power generation. As is illustrated in Figure 2-4 hydrogen from SMR has a footprint of >9kgCO_2/kgH_2, while SMR with CCS can reduce this to as low as 1kgCO_2/kgH_2 (DNV, 2021a). The most carbon-efficient blue hydrogen projects thus have the potential to comfortably meet EU taxonomy requirements at present, and will likely remain within requirements until green hydrogen is substantially ramped up.

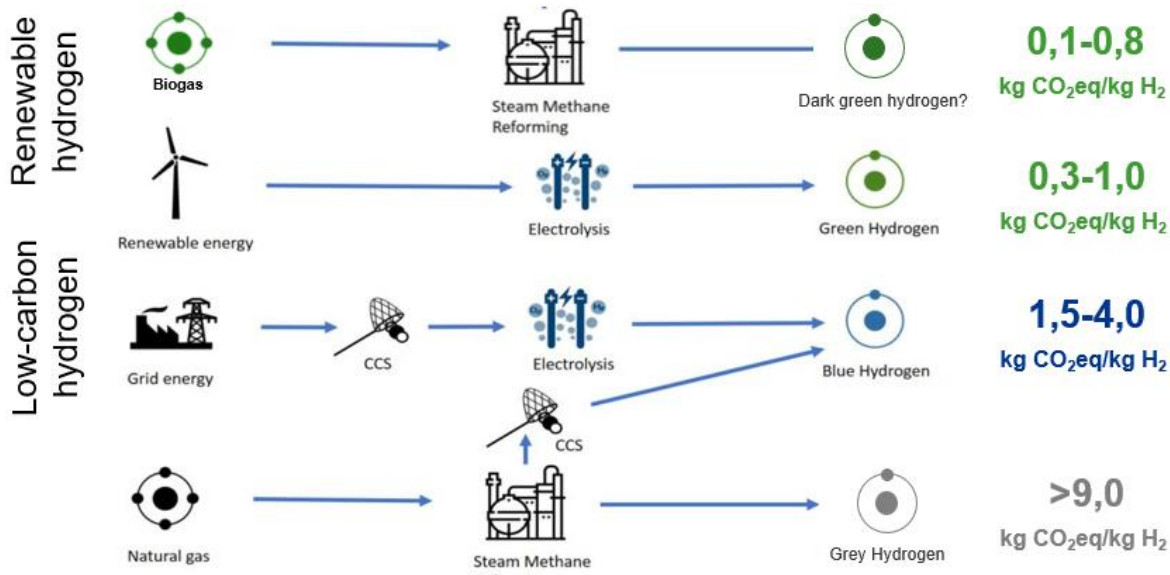


Figure 2-4: CO_2-emissions from hydrogen value chains, approximations (DNV-analysis) (DNV, 2021a)

2.3 Efficiency

Energy efficiencies differ between energy carriers and technologies. There are several analyses of this for road transport, comparing battery electric, fuel cell electric and power to liquid solutions. Performance of electric motors, hydrogen and e-fuels in airplanes still have to be tested further, but the overall picture will likely be similar to the one for road transport. Direct electrification is by far the most efficient solution, both in terms of so-called “well to tank” and “tank to wheel” efficiency, with overall efficiency of around 80% including charging losses (Transport & Environment, 2020). However, batteries are heavy and do not have high enough energy density for long distances and heavy loads compared to conventional fuels. Hydrogen is known for its low weight, but takes up a lot of space. The overall efficiency of using hydrogen for propulsion depends on whether it is used in a fuel cell or in a combustion engine. E-fuels or synfuels have high energy density and can be used directly in existing engines, but the production step consisting of refining CO_2 with hydrogen requires a significant amount of energy (McKinsey & Company, 2020). The exact efficiency comparisons between hydrogen and e-fuels, and electric propulsion with fuel cells and combustion of hydrogen in turbines have to be explored further.

3 LOGISTICS AND VALUE CHAINS FOR HYDROGEN-POWERED AVITATION

3.1 Production and logistics concepts

Hydrogen for aviation can be sourced either through local production by electrolysis from green electricity at the airport or just “outside the fence”, or from a central hub and transported to the airport, as shown in Figure 3-1. Depending on the production technology and whether it should be used in fuel cells or combustion the hydrogen needs to be conditioned to reach the needed purity.

The preferred hydrogen supply solution depends on a wide range of factors, such as transport distance, demand and usage at the specific airport, available space at the airport and the accessibility to feedstock. Storing and transporting hydrogen is expensive, and it is generally economically favorable to produce the hydrogen close to the offtake. The cost of transporting hydrogen versus savings of economies of scale for a large production facility must be valued against each other. In a phase of scaling up, hydrogen can be supplied to the airport from central hubs, before the hydrogen demand is large enough to establish production at the airports.

Airports at locations with strong grid capacity and good access to low-cost renewable power can potentially become hydrogen hubs supplying other offtake. If not produced at the airport, the hydrogen must be compressed or liquified and distributed to the airport through different transport alternatives. At the airport, the hydrogen must be stored and transferred to the airplanes via different distribution methods. Different concepts for fueling or replacing tanks/pods with varying purity for either combustion or fuel-cell electric propulsion is currently being investigated and developed.

Assuming the consumption of Jet-A1 aviation fuel at Norwegian airports such as Bergen, Trondheim, Stavanger is around 70-90 million liter/year, switching 50% of their fuel to hydrogen would require around 1250 tons hydrogen per year, or 3,5 tons per day (by converting energy content and assuming same efficiency). This can be produced locally at the airport or transported from the production hub to the airport. The electrolyser capacity required to produce 3,5 tons hydrogen per day depends on its operating hours – if grid connected and operating almost continuously the required capacity is below 10 MW, while an electrolyser directly connected to local wind and/or solar generation would require a higher installed electrolyser (and storage) capacity. For a grid connected electrolyser sufficient capacity in the grid is crucial, and large-scale green hydrogen production will require grid upgrades, which can be expensive and time consuming. The footprint of a 10 MW electrolyser can vary between 500-1000 m^2, or even more, depending on AE or PEM technology, need for storage, purification and compression steps, water desalination and demineralization steps etc. The total space required is highly dependent on safety distances required and needed barriers, which is described in section 3.3.1.

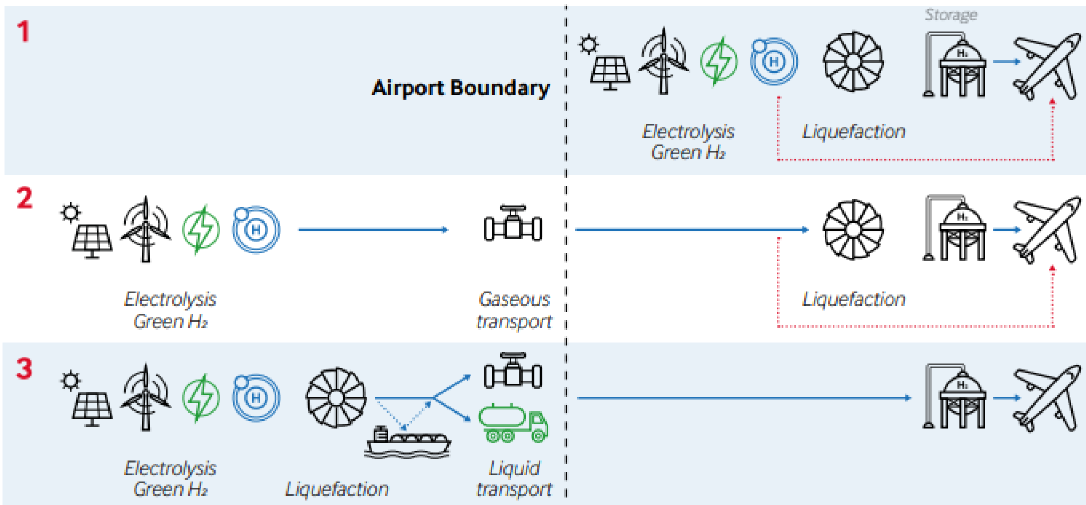


Figure 3-1: Hydrogen supply chain options to the airport (ACI, ATI, 2021)

3.2 Transport

In principle, hydrogen can be transported in either liquid or (compressed) gaseous form via trucks, rail, ships or in pipelines, shown in Figure 3-2. Transport of hydrogen over long distances is expensive - compressed hydrogen mainly due to the low volumetric energy density, liquefied mainly due to costly liquefication. The preferred or lowest-cost option for transport will depend on the hydrogen state. Liquid hydrogen has a higher energy density than compressed hydrogen, and hence more energy is required to liquefy hydrogen than for compressing it. Ammonia (NH3) can be a hydrogen carrier, where hydrogen is combined with nitrogen. Ammonia is a global commodity, and even though it is highly toxic, transport concepts are well known. Ammonia in turn has a higher energy density than liquid hydrogen and can be stored and transported as a liquid at relatively low pressures or in cryogenic tanks, which implies that ammonia can be transported at relatively low cost. However, the required dehydrogenation to release hydrogen from ammonia or a liquid organic hydrogen carrier (LOHC) will use significant amounts of energy and creates a need for additional infrastructure at the point of use. If waste heat is available at the site, this may be beneficial for the dehydrogenation.

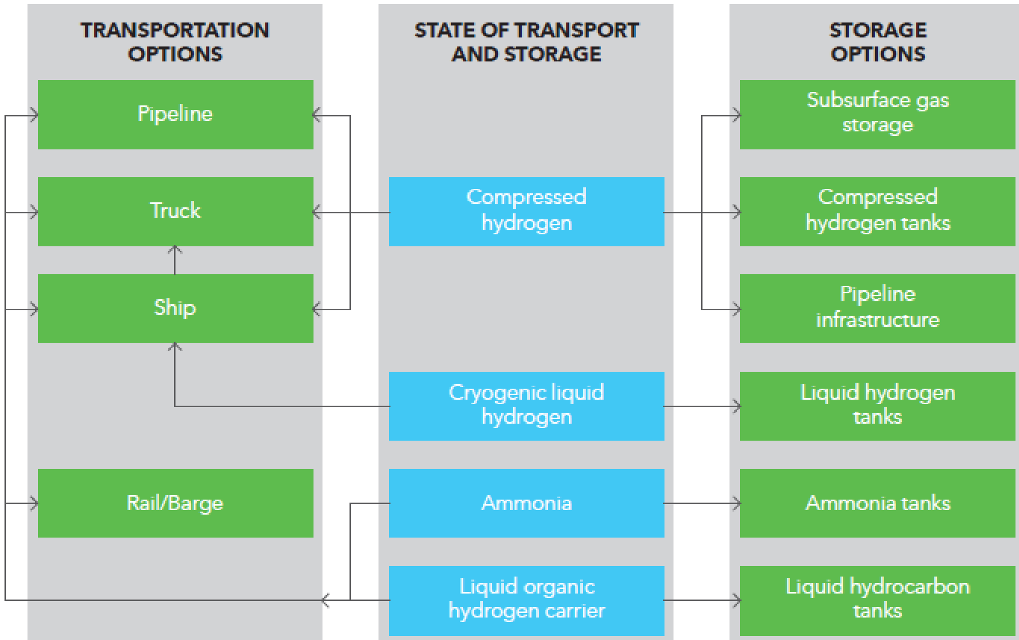


Figure 3-2 Overview of main options for production, transport and storage of hydrogen (DNV GL, 2018)

Generally, pipeline transport of compressed gaseous hydrogen is considered the most cost-effective way of transporting large volumes of hydrogen over long distances, especially if existing gas infrastructure can be utilized either with small percentages of blending or retrofitting to dedicated hydrogen pipelines. Norway has few onshore gas grid pipelines, limiting this possibility. For small volumes, such as those in use today at hydrogen fuelling stations, transportation in bulk by truck is generally considered to be most cost-effectively option.

If hydrogen is not produced locally at the airport, the transport options most suitable in a Norwegian context are:

- Pipeline from a hub to the airport, if distances are less than "a few hundred or thousand meters", preferably "just outside the fence"
- Trucks with swap containers or tube trailers of compressed (or liquified) hydrogen from a nearby electrolysis facilities within a certain distance, <150 km or 2 hours of driving. This may also be done for shorter distances with pods (composite tanks inserted and replaced for each flight instead of refueling with hose and dispenser)
- Liquefied hydrogen by ship from a large hub, if the airport is in proximity of a harbor where it is suitable to deliver the hydrogen
- Hydrogen carrier by ship, such as ammonia or LOHC, to be released back to hydrogen and purified. If transported by ship, it can be moved large distances without adding much to the cost, so the hydrogen carrier can be part of a national or global trade of e.g. high or low grade ammonia, if other hydrogen local use also is an offtaker, or if no local, but regional ammonia is produced (e.g. from North of Norway to Bergen)

3.3 Storage and distribution at the airport

Once the hydrogen has been transported to the airport (or locally produced) it must be cleaned and purified if needed, then stored and distributed to the aircraft. Hydrogen is an ultra-light gas that will take up substantial storage space under standard pressure. For it to be efficiently stored as pure hydrogen, its volume hence needs to be reduced. Generally, four options exist:

- High-pressure storage in gaseous form in tanks (350-700 bar)
- Very low, cryogenic (−252.8°C) temperature storage in liquid form
- Hydride-based storage in solid form, on the surface of solids (adsorption), or within solids (absorption)
- As a hydrogen carrier (ammonia if combined with nitrogen, LOHC if combined with oils, e-methanol if combined with CO_2)

Currently, hydrogen is typically stored in gaseous form in compressed gas tanks, which require a relatively large footprint. Stored in this form, even if compressed at a high pressure of 700 bar, hydrogen would take up nearly seven times the space of an equivalent energy amount of conventional jet fuel. If stored in liquid form, hydrogen would occupy close to four times the space of jet fuel (ACI, ATI, 2021). Space availability may hence be a limiting factor at some airports.

Due to few options for large-scale cost-efficient hydrogen storage in Norway, such as an existing onshore gas grid or salt caverns, other means of storage should be explored. For the time being, low-cost stranded wind power in the North of Norway can make the business case for ammonia as a hydrogen carrier attractive for storage and transport. Ammonia production is planned for the ammonia commodity markets from wind power in Northern Norway, but also at a large scale as blue ammonia from natural gas with carbon capture. These ammonia production value chains can be a supporting part for storing hydrogen as back up for releasing hydrogen, due to the cost and risk optimization of minimizing hydrogen storage.

However, there has to be a certain high-pressure storage for refuelling the aircraft fast when the plane is disembarking and reloading luggage. The time to fill up the tanks depends on the pressure difference, and as much as 350 bar or even 750 or higher can be necessary for both containing the sufficient energy and filling fast enough for the next flight. Longer duration or overnight slow filling could be explored as an option for some of the planes. Slow filling is relevant for reducing high pressure compression and storage costs and risks. With slow filling, high power demand from the power grid may be reduced, together with fewer installed high-capacity electrolysers.

Distribution of hydrogen at the airport to the aircraft, either in gaseous or liquid form, could be achieved through trucks, pipelines or new unconventional methods such as refuelling platforms, hydrogen pods or fuelling stations. Figure 3-3 shows potential hydrogen distribution inside the airport.

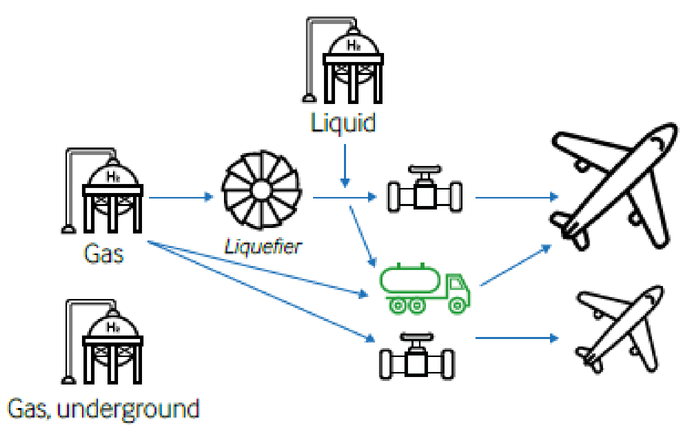


Figure 3-3 Hydrogen supply chain at the airport (ACI, ATI, 2021).

Each of these options will create unique requirements and challenges for the airport industry, in terms of infrastructure, operations, safety, and costs implications. For example, using hydrogen pods, which in practice would mean a replaceable hydrogen tank in the aircraft, would require special service vehicles, storage solutions and safety considerations. Pipelines are in use for conventional jet fuel at some airports today and could potentially be repurposed for hydrogen (ACI, ATI, 2021). However, given the current infrastructure in place, space constraints and the required investments for retrofitting, the most viable near-term option is likely to be using refuelling trucks. Smaller regional airports could potentially be better placed to facilitate this, where similar trucks are already in use today, whereas at larger airports the increase in traffic may raise safety concerns and create logistical issues (McKinsey & Company, 2020). Learnings from the military, aerospace and rocket launch industry would be important for the civil aviation sector for choosing cost-effective and safe solutions.

3.3.1 Safety

One very important part of storing and using hydrogen is the safety and risk aspect. Hydrogen is a highly explosive gas, and leakage from hydrogen storage tanks can lead to fatal consequences. Certain safety distances between hydrogen storage and other infrastructure must be complied, and a zone map shall be part of the required explosion prevention documentation with zone classifications (0–1–2). A 5 tonnes permanent compressed hydrogen storage can require safety distances of 60 meters in all directions depending on the type of storage, physical barriers and pressure levels, as well as landowner and type of neighbours. Installations harbouring more than 5 tons capacity require application for special consent from the Directorate for Civil Protection (DSB).

Hence, finding enough available space at a potential production site can be a challenge. Even though the space required for only the storage tanks are several times the equivalent space for jet fuel, the required space for the hydrogen storage is largely decided by the safety distances. The total space required for a 10-20 MW electrolyser with a 5 tonnes storage, including safety distances, can be more than 15 000 m^2. However, at an average regional Norwegian airport, potential hydrogen volumes, storage requirements and required safety distances will probably be lower than this. Transportable containers (such as trailers), with possibility to connect and disconnect fuel systems will most likely be linked with increased leak frequencies and thus increased safety distances. Risk mitigating measures, such as concrete fire and blast walls around storage tanks with minimum distances and good ventilation even with above mounted (roof) fragment barriers, can reduce the required safety distances. Storing lower volumes of hydrogen in the same location also lowers the risk. Required storage volume depends on fuel demand, logistics solution and security of supply requirements.

Several studies have been undertaken to examine the relative risks of hydrogen as a fuel compared with conventional jet fuel. Overall, they paint a relatively complex picture, as certain characteristics of hydrogen make it less risky, while others make it more hazardous. Having said that, the risks of hydrogen are unique and new to the civil aviation industry, which means that procedures to eliminate these hazards will need to be adopted. An overview of safety aspects of liquid hydrogen storage at airports is shown in Figure 3-4 (ACI, ATI, 2021).

	Jet A-1	Cryogenic hydrogen, LH_2	Implications
Boiling point (°C)	167-266	-252	Frostbite, hydrogen boil-off, material embrittlement
Flammability Limits (%)	0.6 to 4.7	4 to 75	High likelihood of hydrogen fire, but higher concentration required to start it
Min. ignition energy (mJ)	0.25	0.02	High likelihood of hydrogen fire with weak sparks
Burning velocity (cm/s)	18	265-325	A hydrogen fire would finish faster than a kerosene one
Buoyancy		14x lighter than air, rise at 20 m/s	Gaseous hydrogen disperses quickly
Self ignition Temp (°C)	210	585	Harder to ignite hydrogen with pure heat
Fire heat radiative fraction	30-40%	10-20%	Hydrogen fires could be less destructive, as they radiate less heat, but present challenges due to invisible flame

Figure 3-4: Safety aspects of Jet A-1 fuel compared to liquid hydrogen (ACI, ATI, 2021)

Although these risks are new to the civil aviation industry and will need to be considered in the context of airport operations, hydrogen production, transport and storage is currently manageable in the hydrogen industry. The hydrogen industry produces more than 100 million tonnes of hydrogen per year globally, mostly for fertilizers and refineries. It will hence be important for the aviation industry to absorb key learnings, insights and expertise from the existing hydrogen sector to safely manage the introduction of hydrogen to the value chain.

4 HYDROGEN PROJECTS, PLANS AND POTENTIAL AVIATION SUPPLY IN NORWAY

A rapidly increasing number of actors are planning production and use of hydrogen in Norway; within maritime, industry and road transport. There are more than 30 pilot projects for new hydrogen production in various stages of planning. However, fewer than 15 are estimated in a detailed design phase, where a few are being constructed with a small scale first phase.

National climate targets and plans, public requirements for low emission solutions and support schemes are pushing/incentivizing the development of hydrogen projects. The Norwegian government is strengthening their focus on hydrogen-related research and development, and are considering the establishment of a state owned hydrogen company.

This chapter gives a brief overview of hydrogen projects and plans in Norway, first by linking them to Avinor's airports based on location in 4.1, before some selected projects are described in 4.2 and 4.3.

4.1 Potential hydrogen supply to Avinor's airports

For Avinor to prepare for hydrogen-powered aviation, solutions for hydrogen supply at relevant airports should be in place when the first hydrogen aircrafts come to market. To get an overview of potential suppliers to Avinor's airports, current hydrogen initiatives and airports have been plotted on the same map. There is a rapidly increasing number of hydrogen initiatives all over Norway, both for hydrogen production, hydrogen filling stations and hydrogen driven vessels and vehicles. Figure 4-1 shows an overview of projects and plans for hydrogen production based on DNVs current knowledge, together with Avinor's airports.

The aircraft indicate the location of Avinor's airports and the color of the aircraft show the different airport categories (consult the Appendix for more information about the categories). The color of the bubbles indicates the type of hydrogen production (green or blue hydrogen), while the purple bubbles indicate other hydrogen offtake or hubs. To have a simple indication on size of the projects, a distinction between production volumes has been made, with larger bubbles for the larger projects where planned production volumes are known and are above 1000 tonnes H2 per year. This is just an indication, as production volumes for most of the projects are uncertain or unknown and has not been a focus in this project. The maturity and timeline of the projects vary - some might have been put on hold, while others accelerate with new financing from private and public actors.

The map illustrates that most of the airports are located along the coast, and that the highest density of hydrogen projects is on the southwestern coast, coinciding with the Norway's highest maritime and economic activity related to fossil oil and gas infrastructure.

Table 4-3 provides a closer look at airports in concept A, B and C – the bigger airports in Avinor's network.

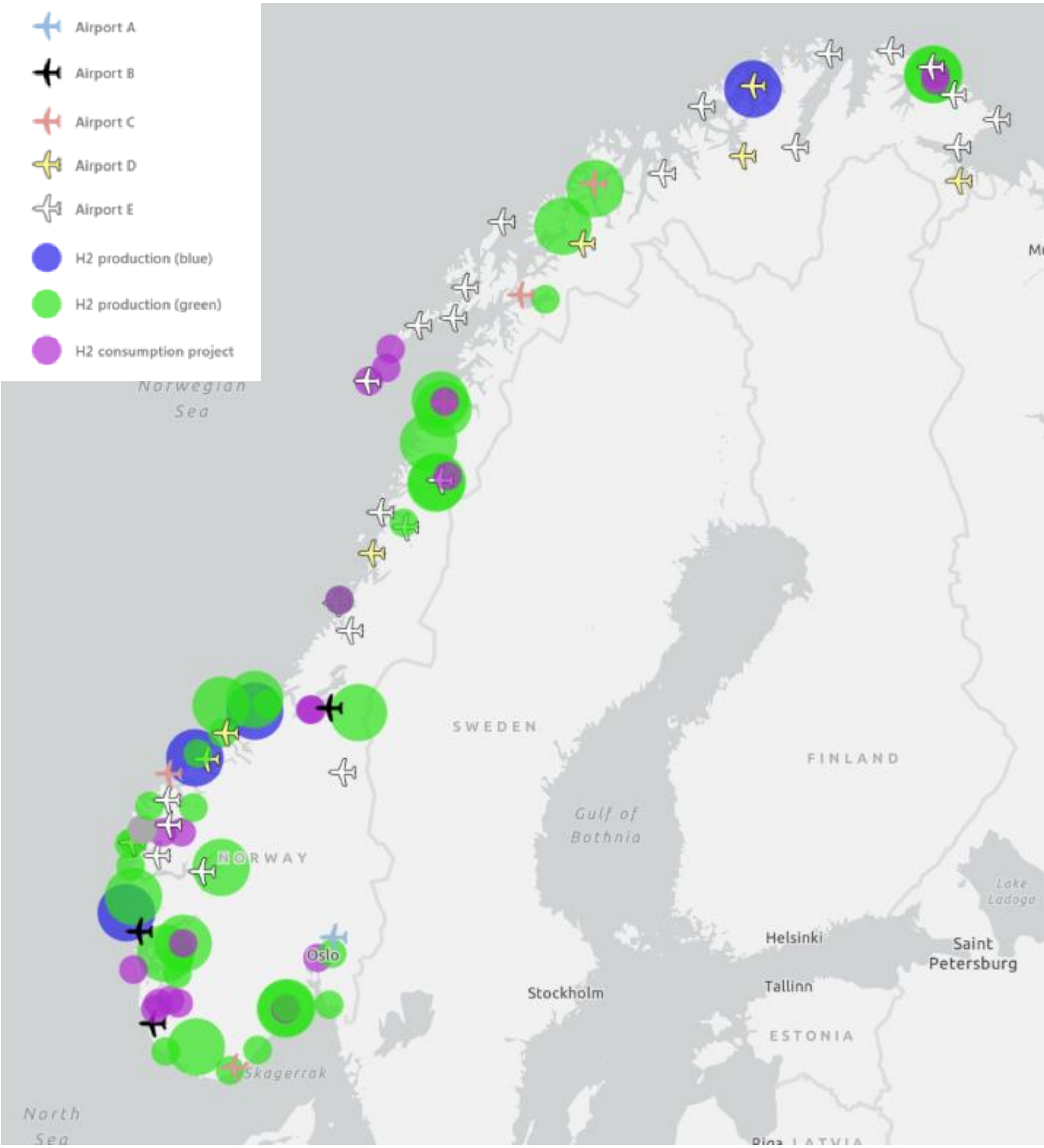


Figure 4-1 Hydrogen projects and Avinor's airports

As described in chapter 3 there are several potential hydrogen logistics solutions and value chains. When identifying potential hydrogen suppliers to airports, the following cases for logistics solutions have been defined based on distance between the hydrogen production and the airport:

- Case 1: Local hydrogen production inside or “immediately outside the fence” with grid or renewable power running an electrolyser, biogas reformer, or small-scale blue hydrogen
- Case 2: Short distance/Immediate proximity (<2 km): Hydrogen transport by pipelines
- Case 3: Medium distance (<150 km): Hydrogen transport by truck with swap containers or tube trailers
- Case 4: Long distance (>150 km) and close to coast/harbor: Hydrogen transport by ship (either liquified or by converting to ammonia)

With focus on airport categories A-C, hydrogen projects and plans that can be potential suppliers to each airport have been identified. Table 4-1 indicates which logistics cases could be most relevant to the airports based on the proximity to existing hydrogen production projects and initiatives (a closer view is shown in Table 4-2). If new hydrogen initiatives appear close to the airports the most relevant logistics solution may change.

Due to the cost of transporting hydrogen, building a smaller electrolyser inside or right outside the fence will probably be the best solution for most airports. Most of the pilot projects are small and in an early development phase, and full-scale production with potential delivery to airports will probably not be relevant within the next few years. Hydrogen production close to airports can also become potential hydrogen hubs with offtake from industry, maritime and heavy road transport. Airports located close to the coast (all except Oslo Gardermoen) are also considered as suitable for case 4, as the demographics can make it difficult to transport by road, and it gives opportunities for long distance transport of hydrogen.

Table 4-1 Suitable logistics solutions for the largest airports, based on location and proximity to existing hydrogen projects

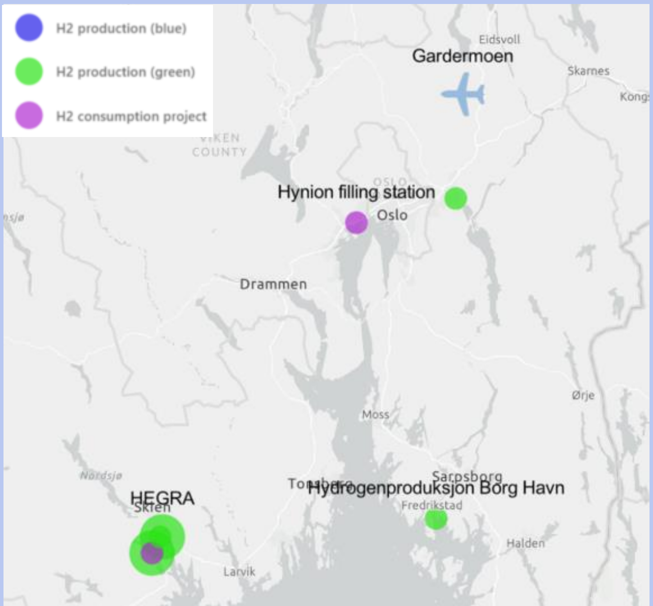
	Airport (category)	**Case 1** **Local H2 production**	**Case 2** **H2 pipeline transport**	**Case 3** **H2 Truck transport**	**Case 4** **H2 Ship transport**
A	Oslo, Gardemoen	✈ (green)	✈ (yellow)	✈ (yellow)	✈ (red)
B	Bergen, Flesland	✈ (green)	✈ (yellow)	✈ (green)	✈ (green)
	Stavanger, Sola	✈ (green)	✈ (yellow)	✈ (green)	✈ (green)
	Trondheim, Værnes	✈ (green)	✈ (yellow)	✈ (green)	✈ (yellow)
C	Bodø	✈ (yellow)	✈ (green)	✈ (green)	✈ (green)
	Tromsø, Langnes	✈ (yellow)	✈ (yellow)	✈ (green)	✈ (green)
	Kristiansand, Kjevik	✈ (green)	✈ (yellow)	✈ (green)	✈ (green)
	Ålesund, Vigra	✈ (yellow)	✈ (yellow)	✈ (red)	✈ (green)
	Harstad-Narvik, Evenes	✈ (green)	✈ (yellow)	✈ (yellow)	✈ (green)

Table 4-2 gives a closer view on each airport and projects that can be potential hydrogen suppliers and a brief description of relevant logistics solutions. It must be underlined that the bubble size is just an indication of size “small” or “large” where planned hydrogen volumes have been announced and are known, and are not proportional with size. For most of the projects volumes are unknown.

Table 4-2: Potential hydrogen suppliers to airports

<table>
<tr><th colspan="2">Airport (Airport category)</th></tr>
<tr><td>

Oslo Lufthavn, Gardermoen (A)



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Potential hydrogen production nearby

There are currently no large hydrogen projects close to Oslo airport. However, there are several smaller initiatives close to Oslo and Lillestrøm for heavy duty transport. The company Green H2 Norway has announced plans to build a production facility and refueling infrastructure in the Oslo region. The industrial projects are located at Herøya in Porsgrunn (210 km).

Possible logistics solution

Swap containers with transport grade compressed hydrogen from nearby smaller electrolysers (0,5-1 tonne per container) by 2025.

Volumes from the industrial sites at Herøya are also possible to transport by tube trailers or swap containers, but at the edge of viable transport distance.

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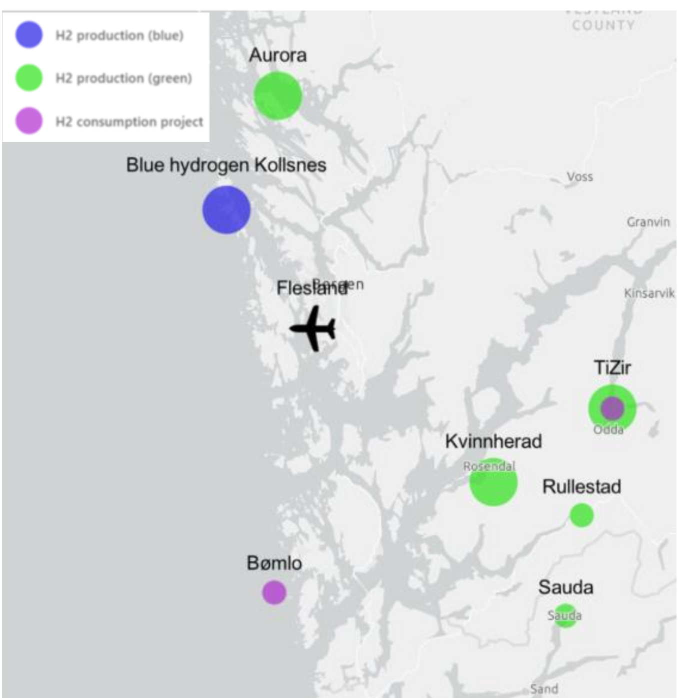
Bergen, Flesland (B)



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Potential hydrogen production nearby

Blue Hydrogen Kollsnes (ZEG and CCB) (53 km): Blue hydrogen production at CCB Energy Park for maritime and road transport.

Aurora project Mongstad (80 km): Large scale green liquid hydrogen production for the maritime sector, initially planned production start in 2024, but project is currently paused.

Possible logistics solution

The large scale planned projects at Aurora and Kollsnes could potentially supply hydrogen in ships as liquefied hydrogen or ammonia for global trade, and deliver to all coastal airports. The logistics concepts could also include tube trailers or swap containers, however with tunnels and ferries the transport option by road is challenging. An electrolyser on site or nearby is more likely a better business case, where also local heavy-duty transport, some industry sites and regional long distance buses with hydrogen range extenders could be relevant.

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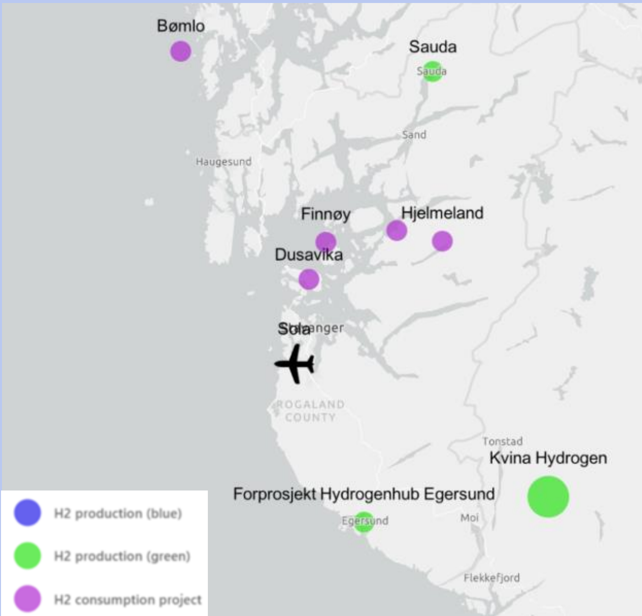
</table>

Stavanger, Sola (B)



Potential hydrogen production nearby

Hydrogenpro og Kvina Energy Park consider building a large-scale green hydrogen production facility (157 km).

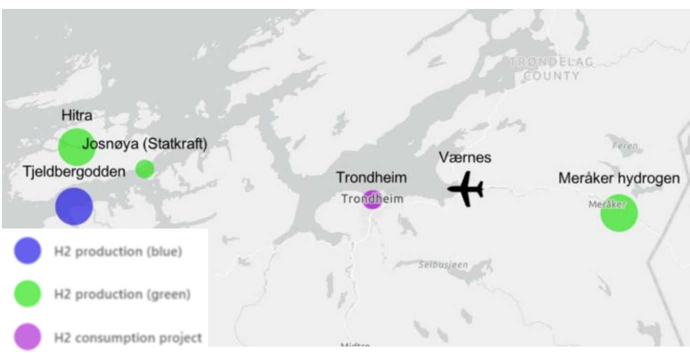
Hydrogen Hub Egersund (Enova pre-feasibility project H2 maritime) (73 km).

Hjelmeland (80 km): The hydrogen hybrid ferry, "Hydra" for Hjelmeland-Nesvik connection, currently fueled by liquid hydrogen from Germany, may in time have local hydrogen production.

Possible logistics solution

Hydrogen can potentially be transported by swap containers from Egersund, Kvina (but probably long distance), or Hjelmeland, if hydrogen production is established. However, these projects are still uncertain.

Trondheim, Værnes (B)



Potential hydrogen production nearby

Meråker hydrogen (50 km) are planning production of up to 10 tons hydrogen per day from 2024.

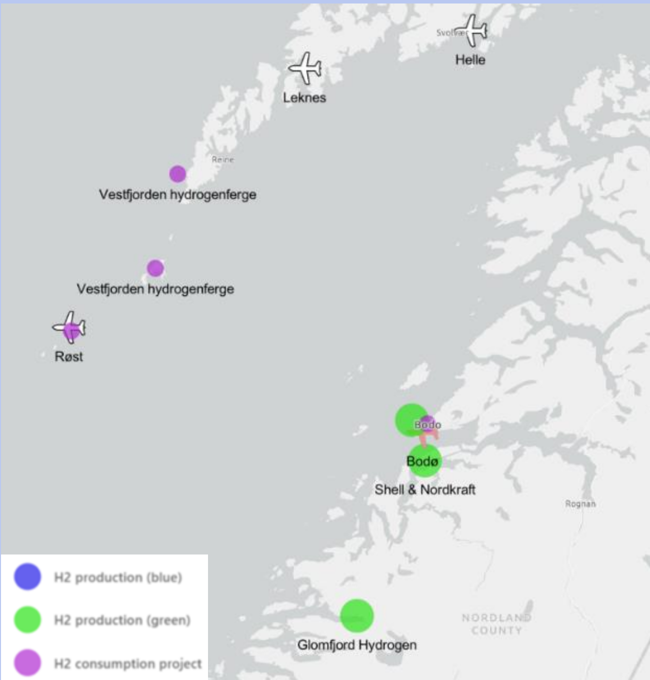
Hydrogenknutepunkt Midt-Norge (Enova pre-project H2 maritime, unknown location).

Possible logistics solution

There are no hydrogen projects in the immediate vicinity of Værnes. Meråker may be a location close enough for swap containers, or potentially rail transport. However, the initiative looks at hydrogen offtake in the entire region.

At the coast west of Trondheim, there are several maritime initiatives, but these may have a more limited transport and logistics arrangement with the airport.

Bodø (C)



Potential hydrogen production nearby

Bodø has several initiatives for hydrogen production for maritime use.

Vestfjorden ferries (Bodø-Lofoten islands) will be hydrogen driven from 2025. Shell and Nordkraft plan a production facility for liquid hydrogen for this ferry connection. GreenH and Linde are also planning liquid hydrogen production for this ferry as well as other potential users.

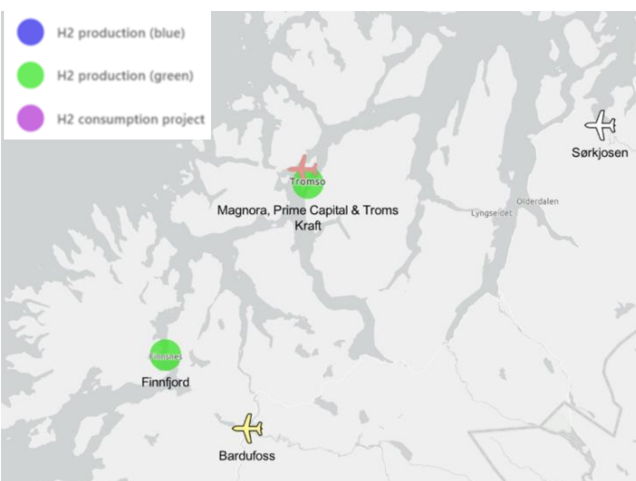
Glomfjord Hydrogen (136 km) can also be a potential supplier.

Possible logistics solution

Options could be pipeline, swap containers, but also “imported” hydrogen by ship as LH2 or ammonia depending on the local production prices and capacity. There are some limits in the existing grids, as for many remote locations, which may limit the amounts of low-cost hydrogen.

Transport of hydrogen with truck from Glomfjord might be possible.

Tromsø, Langnes (C)



Potential hydrogen production nearby

Several planned projects in Tromsø, but also larger scale for exports of green ammonia or for maritime fuel (50/50). Magnora, Prime Capital & Troms Kraft are planning production of green maritime fuel (H2, NH3 and LOHC) in the region.

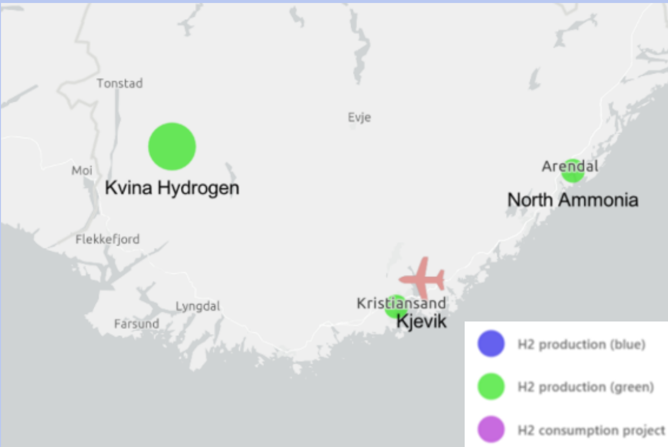
Statkraft, Finnfjord og CRI are investigating possibilities for green methanol production in Finnfjord.

Possible logistics solution

Decent conditions for truck swap containers due to short driving distances from potential production.

Tromsø airport is located seaside, which means good conditions for LH2 or hydrogen carriers.

Kristiansand, Kjevik (C)



Potential hydrogen production nearby

Glencore Nikkelverk (19 km), hydrogenknutepunkt Agder (Enova pre-feasibility project H2 maritime)

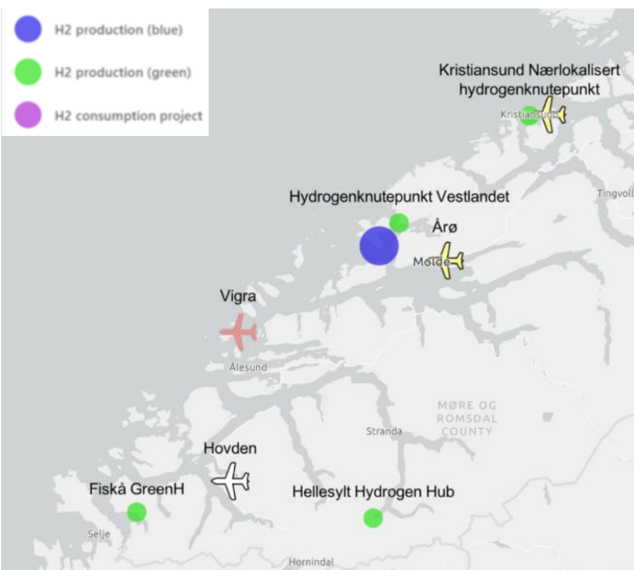
North Ammonia Arendal (66 km)

Kvina Hydrogen (120 km)

Possible logistics solution

Good location for truck transport from hydrogen production at Glencore Nikkelverk

Ålesund, Vigra (C)



Potential hydrogen production nearby

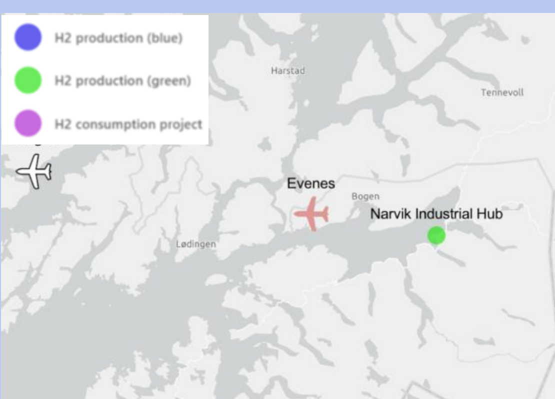
No hydrogen projects in immediate proximity, but the airport is located at the shore side.

Aukra Hydrogen Hub and Hellesylt Hydrogen Hub is in relatively close overhead distance, but road transport requires ferry crossings.

Possible logistics solution

Potential hydrogen deliveries by ship from Aukra. Molde airport is closer to Aukra and has good opportunities for hydrogen deliveries from here.

Harstad-Narvik, Evenes (C)



Potential hydrogen production nearby

No hydrogen projects closeby. However, Aker and Aker Horizons are collaborating with Narvik municipality to establish a new green industrial hub in Narvik, including hydrogen (60 km from Evenes).

Possible logistics solution

Potential for hydrogen transport by swap containers or ship from planned production in Narvik.

4.2 Publicly funded projects

Currently renewable and low-carbon hydrogen production, *and* new off-take solutions and consumption for fuel switching with hydrogen, are significantly more costly compared to fossil alternatives. To support technology development to drive down costs within the whole hydrogen value chain, the Norwegian government has through the state agency Enova (owned by the Norwegian Ministry of Climate and Environment) established several funding schemes, especially for projects within industry and the maritime sector. Several projects receive funding through the Pilot-E funding scheme established by the Research Council, Innovation Norway and Enova (Enova, 2021a). EU with the innovation fund and IPCEI (Important Project of Common European Interest), a pan-European strategic initiative to build joint European value chains for hydrogen, also support projects in Europe, where Enova represents IPCEI for Norway.

In December 2020 Wilhelmsen group received 219 MNOK from Enova to build hydrogen driven ships. Elkem has received 4,4 MNOK from Enova to recover excess hydrogen from their smelter. 27 September 2021 Enova announced that 15 projects have received funding up to 1 MNOK to study the possibility of producing hydrogen from renewable energy for use in maritime sector (Enova, 2021b). These pilot projects will contribute to the development of hubs for hydrogen production along the Norwegian cost. Following this, Enova has announced a new funding scheme targeting hydrogen for maritime applications, offering investment support up to 150 MNOK, with application deadline in April 2022 (Enova, 2021c). To qualify, applicants must have concrete and mature plans to establish production facilities for hydrogen produced with renewable energy. The hydrogen will primarily be made available for maritime transport purposes in Norway, but it can be adapted for multi-use with other sectors.

Furthermore, 17 December 2021, Enova announced that they will support three industry hydrogen projects with more than 1 billion NOK (Enova, 2021d):

- Yara Norge AS will carry out a 24 MW demonstration project (and later 450 MW full scale) at Herøya for production of green ammonia and fertilizers based on hydrogen produced by electrolysis using renewable electricity. The project will be supported with up to 283 MNOK.
- Tizir Titanium & Iron AS will carry out a development and demonstration project for using hydrogen instead of coal to reduce ilmenite at their smelter in Tyssedal. The project will be supported with up to 261 MNOK.
- Horisont Energi AS will through the Barents Blue project establish ammonia production from natural gas with carbon capture near Hammerfest. The project will be carried out by a joint venture established together with Equinor and Vår Energi. The project will be supported with up to 482 MNOK.

The two latter projects are also nominated as Norwegian contributors to the IPCEI hydrogen initiative.

4.3 Overview of current and planned projects

Table 4-3 shows an overview of some of the more advanced developed hydrogen projects in Norway, both for decarbonizing existing grey hydrogen in refineries, methanol and ammonia production, and new green ammonia and direct use of hydrogen for ferries and heavy-duty transport. Some projects are also feasibility studies competing for some of the same offtake, for instance hydrogen ferries. Out of all the feasibility studies, there is a likelihood of not all being completed, or delayed in time awaiting offtake agreements and commitment.

Table 4-3 Selected hydrogen projects in Norway

Project name	Hydrogen category	Planned production start	Initial capacity	Final capacity	Actors
Yara Herøya	Green	2023	3650 tH2/year 20 500tNH3/year	400 000 tNH3/year, approx. 80 000tH2/year	Yara, Linde[1]
Tizir (Tyssedal)	Green			10 000tH2/year	Tizir, Greenstat
Aurora (Mongstad)	Green	Paused[2]	2200tLH2/day		BKK, Air Liquide & Equinor
Barents blue (Hammerfest)	Blue	2025	1 000 000tNH3/year (Approx. 200 000tH2/year)		Horisont Energi, Equinor, Vår Energi
Aukra Hydogen Hub	Blue / Green				Aker Clean Hydrogen, CapeOmega, Norske Shell
Blue hydrogen Kollsnes	Blue	2022/2023	350 tH2/year	5 000 – 18 000 tH2/year	ZEG, CCB
Hydrogen Hub Mo	Green	2023/2024			Statkraft, CELSA, Mo industripark
Berlevåg	Green	2024	15 000tH2/year	30 000tH2/year	Aker Clean Hydrogen, Varanger Kraft
Shell & Nordkraft	Green	2024	5000tLH2/year	10-15000tLH2/year	Shell, Nordkraft
Hellesylt Hydrogen Hub	Green	2023	250tH2/year	330tH2/year	Flakk Gruppen, Hexagon Composites, Hyon, Tafjord, Fiskerstrand Gexcon, Sintef, Stranda
Glomfjord Hydrogen	Green	2024	3000tH2/year		Nel, Greenstat, Meløy Energi, Troms Kraft.

[1] March 29 2022 it was announced that Aker Clean Hydrogen and Stakraft are not pulling out of the project: Yara går videre med Hegra-prosjektet uten Statkraft og Aker Clean Hydrogen (E24)

[2] Hydrogenprosjektet Aurora lagt på is (NTB)

5 NEXT STEPS AND OPPORTUNITIES

Norwegian aviation aims to be a world leader in reducing aviation greenhouse gas emissions and has set a target to be fossil-free by 2050 (Avinor, 2020). As underlined in Avinor's sustainability report, this is ambitious, and Norwegian aviation relies on technology, markets and policies to work together to achieve this target.

Hydrogen has the potential to play a key role in decarbonization of aviation. However, for hydrogen to be a real alternative in the future, increased focus on research, innovation, testing and technology development of hydrogen-propulsion, aircraft systems, and necessary infrastructure must be performed. The cost of hydrogen is still significantly higher than conventional fuel, and effective measures from the authorities and further technology development is required to drive down the hydrogen production cost. More research on risks and safe hydrogen production, transport and storage at airports is also required.

Access to renewable or low carbon hydrogen is expected to be less of a challenge than novel new offtake, as there currently are more hydrogen production initiatives than there are plans for new hydrogen offtake. Production technologies are well known, even though new and more efficient processes are being developed. New production is generally easier to scale than new offtake, rather than replacing fossil "grey" hydrogen. However, the logistics solutions and required infrastructure must be in place. Access to low-cost renewable power, as well as efficient logistics solutions is also essential.

The main challenge for introduction of hydrogen in aviation is the time-consuming certification process of introducing new aircraft. Introduction of larger new aircraft typically takes around 15-20 years, and broad deployment across the fleet another 10 years (McKinsey & Company, 2020). Short-range aircraft can be a steppingstone on the way, and the first hydrogen-driven short-range aircraft is expected around 2035. ZeroAvia signals that their aircraft can be in the market by the end of this decade, and Airbus states that a hydrogen propelled aircraft can be in the market by 2035. Given the long timeline of hydrogen aircraft rollout, hydrogen infrastructure and large-scale hydrogen production may already be built out when hydrogen aircrafts are rolled out. To achieve an efficient hydrogen infrastructure and hub development, synergies and coordination between sectors will be important.

The report *Hydrogen-powered aviation* (McKinsey & Company, 2020) highlights three aspects required to guide the transition in the aviation sector:

- A sector roadmap to guide the transition
- A step-up in research and innovation activity and funding
- A long-term policy framework

Norwegian aviation is well positioned to lead the way in the development of hydrogen-powered aviation and should take initiative to move the above aspects forward. In addition, establishing early dialogue with potential hydrogen suppliers on opportunities for value chains to Norwegian airports will be important, both to support hydrogen production development and for Avinor to be ready for the first hydrogen aircrafts to take off.

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APPENDIX A
Avinor's airports

Avinor is responsible for air navigation services for the civil and military sector, and the 44 state owned civil airports in Norway and operate 42 of them (Fagernes airport is currently without scheduled civil aviation traffic and operations at Haugesund airport is outsourced). Avinor’s airports are as shown in Table A-1, divided into what is termed airport concepts.

Avinor’s network of airports consist of airports with very different sizes and complexities. The intention of the airport concepts is to:

- Categorize comparable airports
- Standardize airports within the same concept in terms of service levels to realize the economies of scale inherent in the network
- Ensure adequate differentiation of services by predefined service levels

Both standardization and differentiation are based on best practice to ensure safety, regularity and cost-efficient operations.

Table A-1: Airport concepts

Concept	Description	Airport
A	International hub that connects the nation to national, international and continental destinations	Oslo (OSL)
B	International airports that connect the region to national and international destinations	Bergen (BGO), Stavanger (SVG), Trondheim (TRD)
C	National airports that connect the region to large cities and selected international destinations	Bodø (BOO), Tromsø (TOS), Kristiansand (KRS), Ålesund (AES), Harstad-Narvik (EVE)
D	Regional airports that connect regions to nodes in the region and supports the need for development within the petroleum industry	Kristiansund (KSU), Svalbard (LYR), Alta (ALF), Kirkenes (KKN), Bardufoss (BDU), Hammerfest (HFT), Brønnøysund (BNN), Florø (FRO), Molde (MOL)
E	Local airports that connect the districts to regional nodes	Lakselv (LKL), Vadsø (VDS), Stokmarknes (SKN), Mosjøen (MJF), Sandnessjøen (SSJ), Sogndal (SOG), Andøya (ANX), Ørsta-Volda (HOV), Leknes (LKN), Svolvær (SVJ), Førde (FDE), Mo i Rana (MQN), Røros (RRS), Rørvik (RVK), Namsos (OSY), Berlevåg (BVG), Båtsford (BJF), Honningsvåg (HVG), Sørkjosen (SOJ), Vardø (VAW), Mehamn (MEH), Røst (RET), Værøy Heliport (VRY)

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