LOGISTICS AND MARKET PREFEASIBILTY STUDY

Hydrogen supply to Norwegian airports

Avinor AS

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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 decarbonizing the Norwegian aviation industry. This version is an update to report number 2022-0463.

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1 INTRODUCTION

The amount of documentation and reports on civil aviation and hydrogen is growing. It is likely that hydrogen will be a relevant energy carrier for future aviation. **The main purpose of this report is 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 aims to provide a brief overview of the current hydrogen landscape in Norway based on existing and public knowledge and 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. Planned projects may get cancelled and new projects will get announced.

The first version of this report was published in April 2022. Since then, a lot has happened - both within hydrogen production plans and within the regulatory space, including terminology and definitions of hydrogen types. Hence, Avinor saw a need for an update of this report around year end 2023, with a focus on changes in planned production projects.

Hydrogen and hydrogen derivatives are widely recognised as an important facilitating energy carrier to enable the energy transition, and particularly in decarbonising hard-to-electrify sectors of the economy, such as industry and long-distance transportation. The production of renewable (or "green") hydrogen is currently in most cases reasonably far off reaching cost-parity with hydrogen produced from fossil gas ("grey" hydrogen). However, several countries have recently released strategies setting targets and committing resources to bring the cost *and* emission intensity of hydrogen production down. For example, the EU is taking a leading position in establishing a market for hydrogen. The EU Hydrogen Strategy was adopted in 2020, and suggested policy action points in 5 areas: investment support, production and demand support, creating a hydrogen market and infrastructure, research and cooperation, and international cooperation. It also set ambitious targets for renewable hydrogen production (10 million tonnes annually) and electrolyser capacity (40 GW) by 2030 in the EU. Additionally, several EU countries, for example Germany, Sweden and Denmark have released their own 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. In 2023 The Norwegian Confederation of Trade Unions (LO) and the Norwegian Confederation of Business (NHO) published a proposal for a new ambitious Norwegian hydrogen strategy[1].

To facilitate the creation of a European hydrogen market, the European Hydrogen Bank was announced in 2022, and the first pilot auction supporting renewable hydrogen production in EU and EEA was launched on the 23rd November 2023. A second auction will open during spring 2024. In October 2023 the new Renewable Energy Directive (RED) was adopted, which sets an ambitious target of renewable hydrogen use in industry. The EU also recently adopted Delegated Acts defining Renewable Fuels of Non-Biological Origin (RFNBO), including renewable hydrogen. ReFuelEU Aviation have set binding blending mandates for sustainable aviation fuel (SAF) for members states from 2025, including a sub mandate for synthetic fuels derived from renewable hydrogen from 2030.

All the recent activity 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:

[1] https://www.nho.no/siteassets/prosjekter-og-samarbeid/energi/rapport-hydrogenstrategi-a4-ny-oppslag-web.pdf (In Norwegian)

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

Direct use of hydrogen in aviation may be a niche in aviation in the medium term (after 2030), then an addition to Sustainable Aviation Fuel (SAF) long term (after 2040), either as fuel cell propulsion or hydrogen combustion in jet engines. Even though there are strict requirements on the input factors of SAF (such as not creating new CO_2 emissions by using biogenic or industrial CO_2), SAF still emits CO_2, and should only be used where electrification or hydrogen are not viable solutions.

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 SAF 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). ZeroAvia develops hydrogen-electric aircraft engines and targets a 550 km range 9-19 seat hydrogen-powered aircraft by the end of 2025 and a 200+seat 9000 km range aircraft by 2040 (ZeroAvia, 2023).

Use of hydrogen as an energy carrier in aviation will impact the aviation eco system, however limited before scaling up. In 2022 the European Commission initiated The Alliance for Zero-Emission Aviation (AZEA) – a voluntary European initiative of private and public stakeholders to prepare the entry into commercial service of hydrogen-powered and electric aircraft. Another example is the Baltic Sea Region (BSR) HyAirport Project which was recently announced – a collaboration between 16 international partners and 24 associated organizations working together to develop the necessary infrastructure for implementing flight connections with hydrogen-powered aircraft around the Baltic Sea (Hamburg Airport, 2023).

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 in Norway 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 renewable (green) hydrogen. Norway's gas reserves, large share of renewable electricity production, relatively 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. After the EU's latest definition of renewable hydrogen, Norway's electricity grid with >90% renewables give a significant comparative advantage for grid-connected hydrogen production. 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

2.1 Status of hydrogen production in Europe

As of 2022, Europe has around 11.5 million tonnes of operational production capacity spread across more than 500 sites and serving around 8.7 million tonnes of demand. These sites emit over 80 million tonnes of CO_2 per year into the atmosphere. Figure 2-1 shows hydrogen production facilities, divided by production method: renewables with electrolysis, fossil fuels with carbon capture, and fossil fuels with release of CO_2. Today, more than 99% of all operational hydrogen production capacity in Europe use fossil fuels as feedstock, mostly fossil gas, and emits CO_2 directly into the atmosphere. The remainder use either grid power or dedicated renewables.

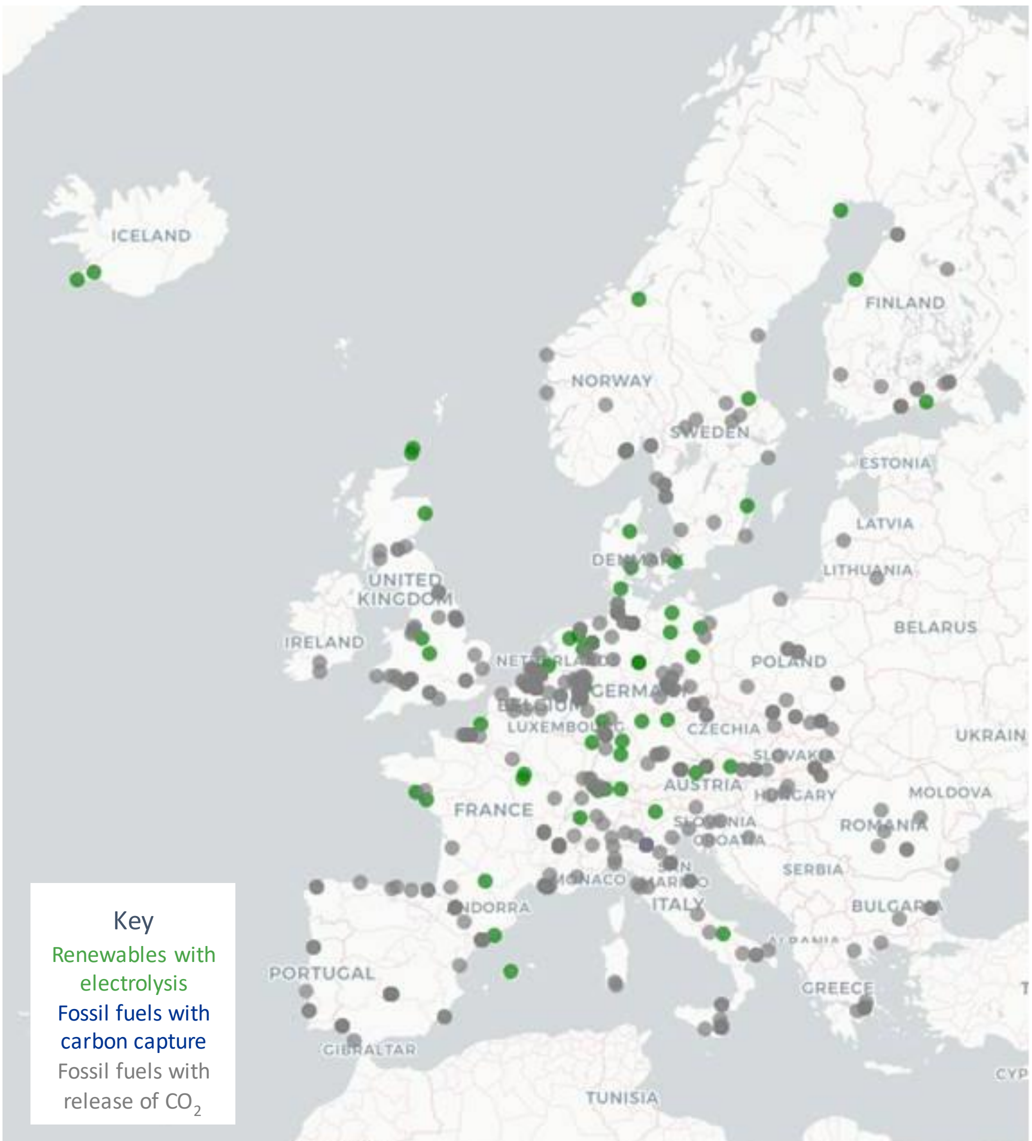


Figure 2-1: Hydrogen production in 2022 (Hydrogen Europe, 2022)

2.2 Types of hydrogen

Hydrogen can be produced via several different methods and technologies, with a variety of feedstocks and energy sources. These different hydrogen production pathways have generally been referred to by colour, of which the most frequently used colours are grey, blue, and green. However, due to a lack of agreement on the definition of each colour, many organizations are moving away from using them and instead looking to a combination of production pathway and/or carbon intensity. The EU has adopted the terms fossil hydrogen, low-carbon hydrogen, and renewable hydrogen. The key criteria to qualify as either low-carbon or renewable hydrogen is a 70% greenhouse gas emission reduction compared to fossil hydrogen. The definitions are given below and will be used in this report.

- **Renewable hydrogen:** Hydrogen made using renewable electricity or reforming biogas. The EU REDII Delegated Act (adopted February 2023) defines Renewable Fuels of Non-Biological Origin (RFNBO), i.e. hydrogen and fuels made using renewable electricity, which meets the GHG emission reduction criteria of 70%, i.e. 3.4 kg kgCO_2e/kgH_2. This is what is referred to in this report as “renewable” hydrogen. RFNBO hydrogen is often called green hydrogen.
- **Low-carbon hydrogen**: Hydrogen produced from non-renewable sources, either using non-renewable electricity or fossil fuels with carbon capture and storage (CCS), which meets the GHG emission reduction criteria of 70%, i.e. 3.4 kg kgCO_2e/kgH_2. Low-carbon hydrogen from fossil fuels with CCS are often called blue hydrogen. Hydrogen produced using non-renewable electricity but is still able to meet the GHG emission reduction criteria qualify as low-carbon – this is especially relevant for nuclear-based hydrogen production.
- **Fossil hydrogen:** Hydrogen not qualifying as renewable or low-carbon, often derived from steam methane reforming without CCS and is often called grey hydrogen.

The definitions of RFNBO and low-carbon hydrogen and fuels are used together with EU mandates for decarbonization in industry, maritime and aviation sector – the hydrogen or fuel used must qualify towards these definitions to count towards the fuel switch, blending or emission reduction mandates.

While the EU has defined criteria and GHG thresholds for renewable and low-carbon hydrogen, there are no global standards on this. The World Business Council for Sustainable Development (WBSD) has in defined the terms “reduced carbon hydrogen (<6 kg kgCO_2e/kgH_2), low-carbon hydrogen (<3 kgCO_2e/kgH_2) and ultra-low-carbon hydrogen (<1 kgCO_2e/kgH_2H2) (wbcsd, 2021)). The US standard for clean hydrogen sets a threshold of 4 kgCO_2e/kgH_2, which has to be met to receive tax credits under the Inflation Reduction Act (IRA).

2.3 Renewable hydrogen

Renewable 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 renewability and carbon footprint of the electricity consumed dictates whether the hydrogen produced is renewable, low-carbon or fossil. The reformation of biogas, on the other hand, uses various carbon capture technologies with a renewable gas feedstock. DNV’s Energy Transition Outlook 2023 (ETO) expects renewable hydrogen to take close to 50% of the market share by 2050.

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 as stack degradation timeframe. There are, at present, four main electrolysis technologies;

- Alkaline Electrolysis (AE), which has been widely used for niche small scale hydrogen production during 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 using steam and electricity, with relatively high efficiency when combined with further high temperature processes
- 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).

Renewable hydrogen was first produced at an industrial scale in Norway 100 years ago and dominated until fossil gas-based hydrogen production took over. Renewable hydrogen generally has a higher cost compared to emission intensive fossil hydrogen, but as the costs of electrolysers and renewable electricity decrease, and the cost of emissions increases, it is expected to become cost competitive with fossil-based hydrogen around 2030. Renewable hydrogen also has the benefit of not relying on the large-scale build-out of infrastructure to deal with emissions as low-carbon hydrogen with CCS does.

The EU generally favours renewable hydrogen in its 2030 targets, however it also leaves space for low-carbon hydrogen. Germany, the biggest potential demand centre, is looking to import fossil-based hydrogen with CCS from Norway in the future. According to DNV’s Energy Transition Outlook 2023, hydrogen production will more than triple up to around 40 million tonnes per year in the 2030s, mostly due to renewable hydrogen with a very small increase in fossil-based low carbon hydrogen, shown in Figure 2-2.

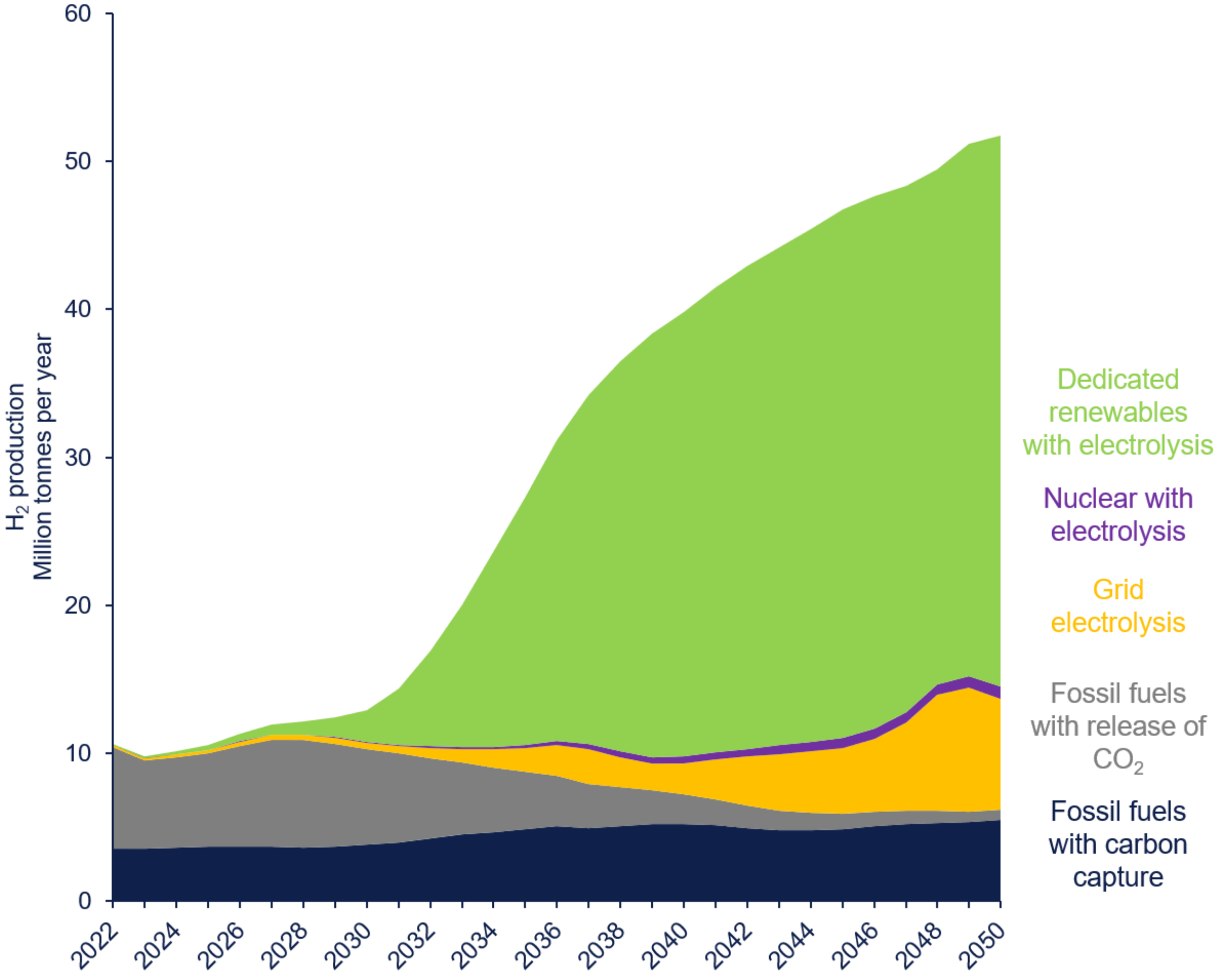


Figure 2-2: European hydrogen production by production route (DNV, 2023)

Ramping up renewable 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 has increased significantly over the past few years, with the EU ETS price trebling over 2021 from EUR 30/ton to over EUR 90/ton (which is about the current level end of 2023), 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:** Cost-competitive renewable electricity is a prerequisite for the rollout of renewable 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 renewable 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 renewable hydrogen capacity targets, and the EU has set a renewable 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 renewable hydrogen and fossil solutions, the first mechanism in the EU now being the European Hydrogen Bank pilot auction, following after the US IRA with tax credits.

2.4 Low-carbon hydrogen

According to DNV's Energy Transition Outlook 2023, low-carbon hydrogen from SMR with CCS is expected to gain a significant global market share by 2050 (28%) due to decreased costs and higher carbon prices. The volatility of gas prices increases risk for blue hydrogen projects, but in gas producing regions with access to cheap natural gas such as North America this will have less of an effect than in gas importing regions.

Low-carbon hydrogen involving CCS faces multiple other challenges. CCS technology is still evolving, and concerns about long-term storage, cost uncertainties, and limited economies of scale hinder its rapid deployment. Additionally, achieving CO2 capture rates above 90% remains economically unviable, making low-carbon hydrogen with CCS less competitive compared to other low-carbon and renewable alternatives in the medium to long term. As the scale of upstream methane emissions from fossil gas production is becoming apparent with new satellite technology, the effectiveness of the technology for emissions reductions is also being questioned (U.S. Department of Energy, 2023), see Figure 2-3.

However, countries with large fossil fuel reserves, such as Norway, tend to lean towards formulating hydrogen strategies that focus on low-carbon hydrogen. These strategies naturally also focus on facilitating the capture and storage of carbon, in Norway's case building on existing CCS capabilities and opening storage opportunities for emitters from other countries.

2.5 Emissions intensity

The carbon intensity of hydrogen is highly dependent on the source of energy used to run the process as well as the feedstock from which the hydrogen is produced and its upstream emissions. A recent analysis from US Department of Energy (DOE) investigated the carbon intensity of hydrogen production methods involving CCS in the US. It showed higher emissions intensities than expected – none of them meeting the US "clean hydrogen" criteria of 4 kgCO2e/kgH2 - see Figure 2-3. This production achieved around 60% CO2 capture rate, but the report stated that even with high capture rates life cycle emissions are expected to be higher than the clean hydrogen criteria.

The International Energy Agency has also assessed emissions intensities for various hydrogen production pathways. Hydrogen with 100% renewable electricity with no associated emissions results in an emissions intensity of close to 0 $kgCO_2e/kgH_2$. Where grid electricity is used, this intensity can vary depending on the source and time of day the electricity is used. In regions with high amounts of coal on the grid the emissions intensity can be higher than fossil sources of hydrogen. IEA numbers are also in agreement with those from DOE for CCS applications since midstream and upstream emissions can represent 1 - 5 $kgCO_2e/kgH_2$ on top of the remaining process emissions. In these cases, achieving very high capture rates is key to lower emissions intensities, however to date this has not been achieved at commercial scale and does not address the midstream and upstream emissions. As described above, to qualify as RFNBO or low-carbon hydrogen in the EU, the emissions must be less than 3.4 $kgCO_2e/kgH_2$.

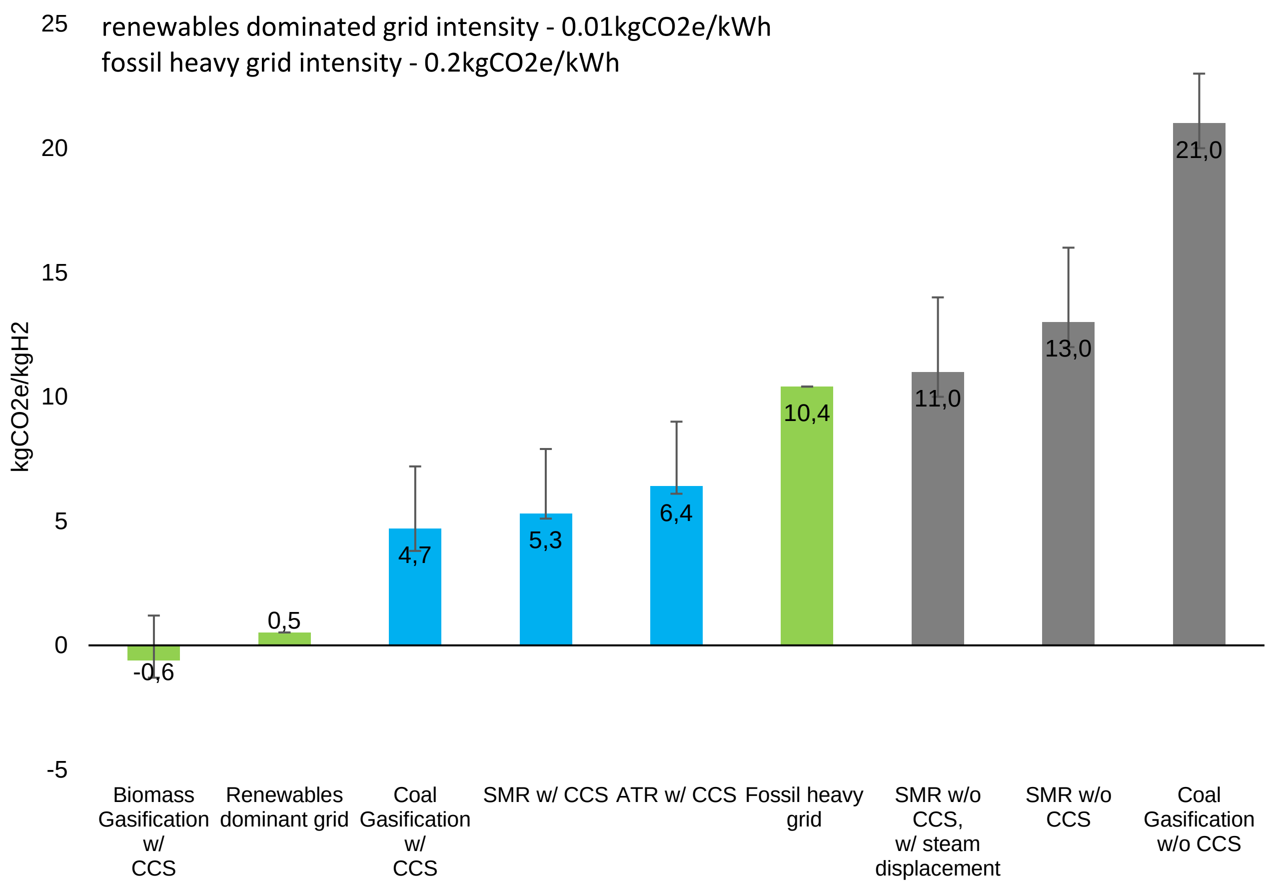


Figure 2-3: Emissions intensity of different hydrogen production pathways. Fossil-based hydrogen with and without CCS (U.S. Department of Energy, 2023), grid electrolysis numbers from DNV modelling.

2.6 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 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 medium and long-distance aviation. 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 a combustion engine. E-fuels or synfuels have high energy density and can be used directly in existing engines, but both the production step consisting of refining CO_2 with hydrogen and burning the fuel in a combustion engine requires a significant amount of energy.

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 renewable electricity at the airport or just “outside the (airport) 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, as well as pressurized to a certain level, or liquefied if needed, depending on the aviation refueling and offtake systems.

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 offtakers. 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 a Norwegian airport such as Bergen, Trondheim, Stavanger is approximately 70-90 million liter/year, switching 5% of their fuel to hydrogen would require about 1150 tons hydrogen per year, or 3 tons per day (by converting the energy content at lower heating value – LHV, 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 tons hydrogen per day depends on its operating hours – if grid connected and operating almost continuously the required capacity is 7-10 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.

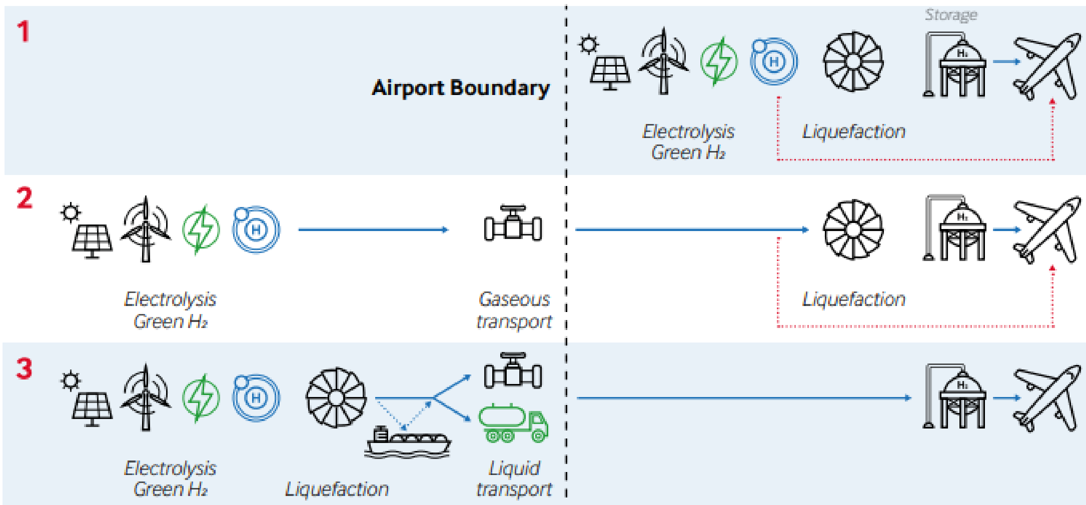


Figure 3-1: Hydrogen supply chain options to the airport (ACI, ATI, 2021)

3.2 Transport

Hydrogen can be transported in either liquid or (compressed) gaseous form via trucks, rail, ships or in pipelines, as 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 (NH_3) 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.

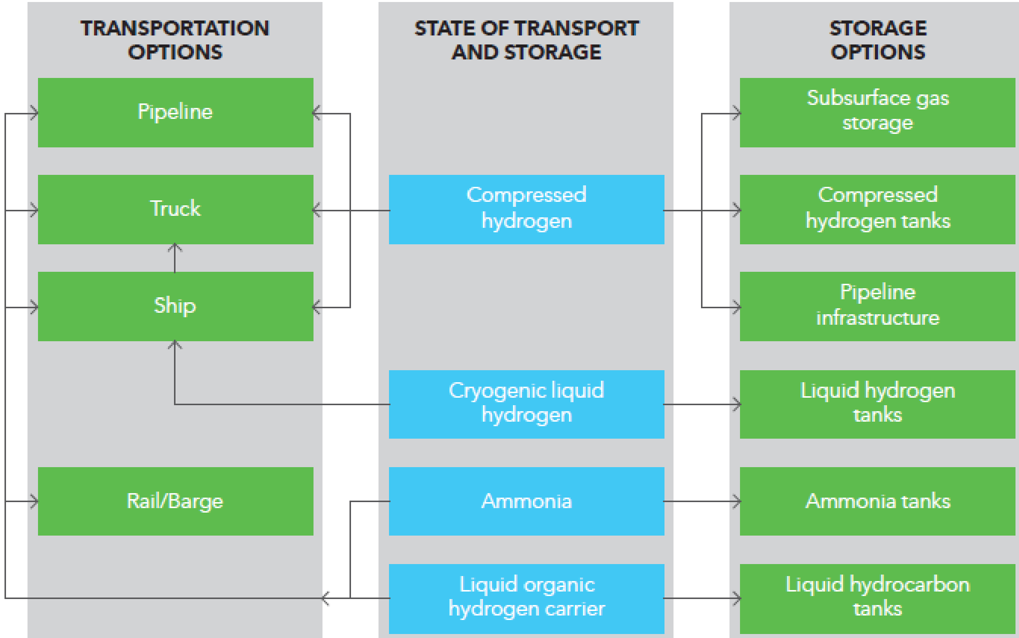


Figure 3-2 Overview of main options for production, transport and storage of hydrogen (DNV GL, 2018)

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 airport 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, cracked and conditioned back to hydrogen and purified. If transported by ship, it can be moved large distances and stored in long periods without adding much to the cost, so the hydrogen carrier can be part of a national or global trade of e.g. ammonia, combined with other local hydrogen use, 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 hydro power and wind power in Western and Northern Norway, but also at a large scale as blue ammonia from fossil 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 aircraft. 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.

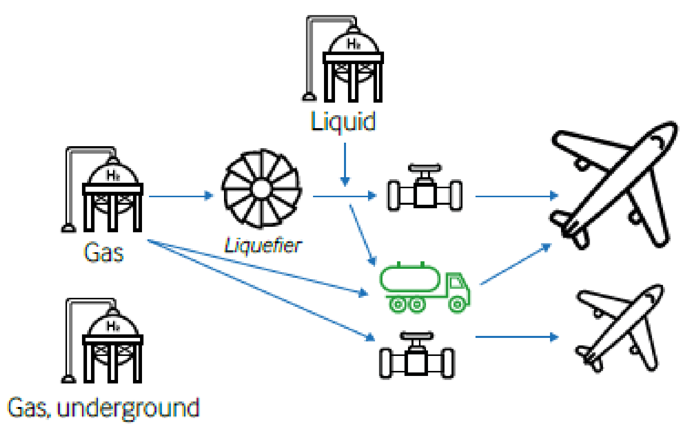


Figure 3-3 Hydrogen supply chain at the airport (ACI, ATI, 2021).

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. The Norwegian Hydrogen Forum has made an updated overview of the Norwegian Hydrogen Landscape (Norwegian Hydrogen Forum, 2023), which includes planned and existing hydrogen production projects, as well as consumption projects (including fueling stations), R&D and technology development projects.

The overview shows that, as of November 2023, there are more than 50 projects for new hydrogen, ammonia and e-fuels production, where almost 40 of these plan hydrogen as their end product. 3 of these plan low-carbon (blue) hydrogen from fossil gas with CCS, while the rest is renewable (green) hydrogen from electrolysis. The projects are in various stages of planning – according to the overview 2 of the projects are in operation, while 4 have reached final investment decision or is under construction. Most of the projects are in the pre-feasibility or feasibility phase.

National and EU climate targets and plans, public requirements for low emission solutions and support schemes are pushing/incentivizing the development of hydrogen projects. However, common across all projects is the need to secure offtake agreements before making final investment decision (FID). Costs of hydrogen are high compared to fossil solutions, and the offtake market is still not established. The Norwegian hydrogen industry has expressed disappointment in the lack of Contracts for Difference (CfD's) from the government (Norwegian Hydrogen Forum, 2023).

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. Figure 4-1 shows an overview of projects and plans for hydrogen production and consumption based on Norwegian Hydrogen Forum and DNV's knowledge, together with Avinor's airports. In addition to the plans for pure hydrogen production, ammonia and e-fuels projects have also been included – as hydrogen production is the first step and could potentially be an end product in these projects as well.

The aircraft indicate the location of Avinor's airports and the size of the aircraft show the different airport categories (consult the Appendix for more information about Avinor's airport categories). The colors of the bubbles indicate the type of production: e-fuels, hydrogen (renewable or low-carbon) and ammonia (renewable or low-carbon). The blue icons for consumption distinguish between road transport, maritime and industry. The road transport icon represent either planned hydrogen fueling stations or initiatives for hydrogen trucks. 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 4-2 provides a closer look at airports in concept A, B and C – the bigger airports in Avinor's network.

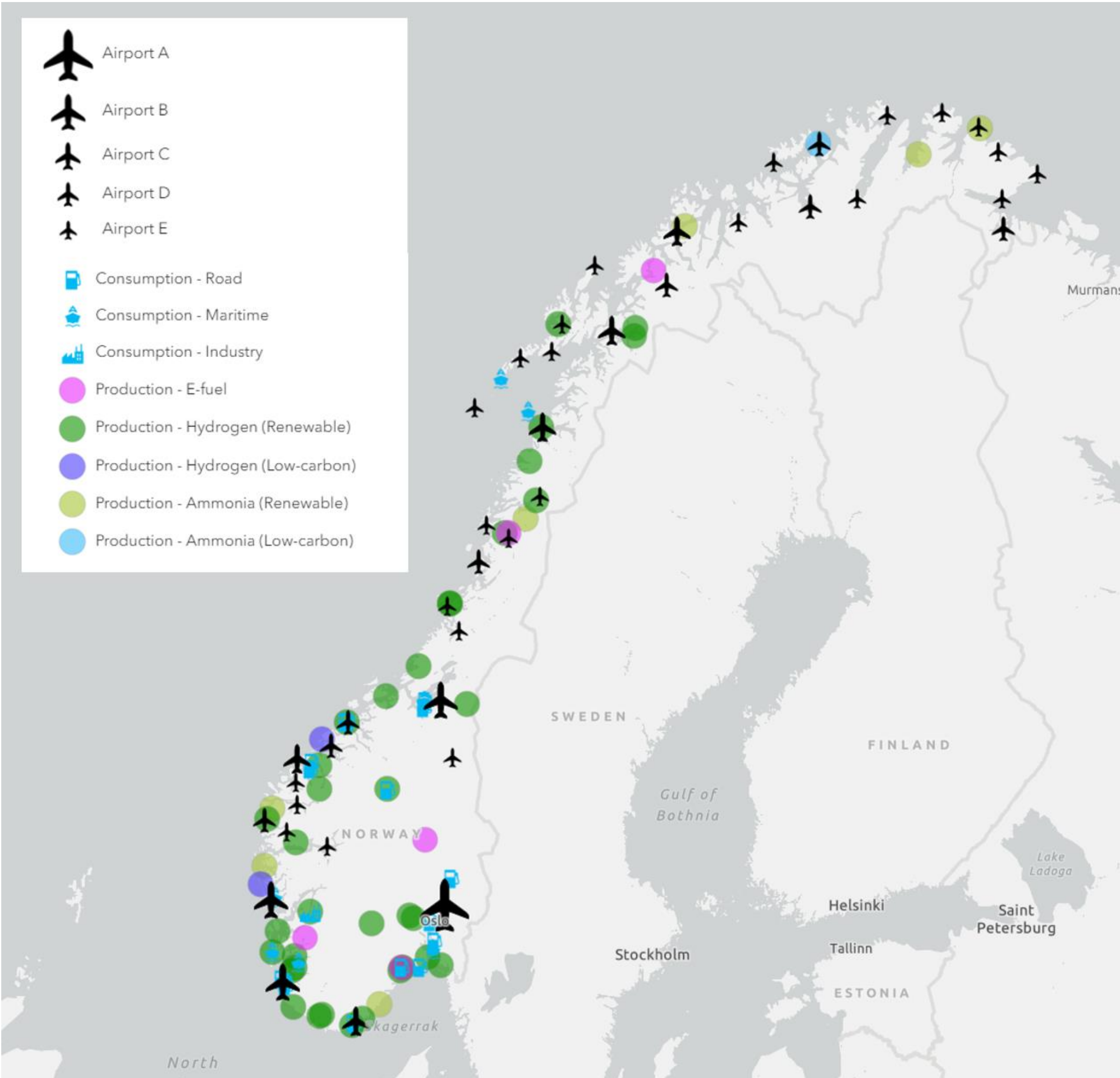


Figure 4-1 Hydrogen projects and Avinor's airports (Norwegian Hydrogen Forum, Avinor, DNV)

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 airport fence

- 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 some of Avinor's bigger 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 airport 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 (hydrogen transport by ship) 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

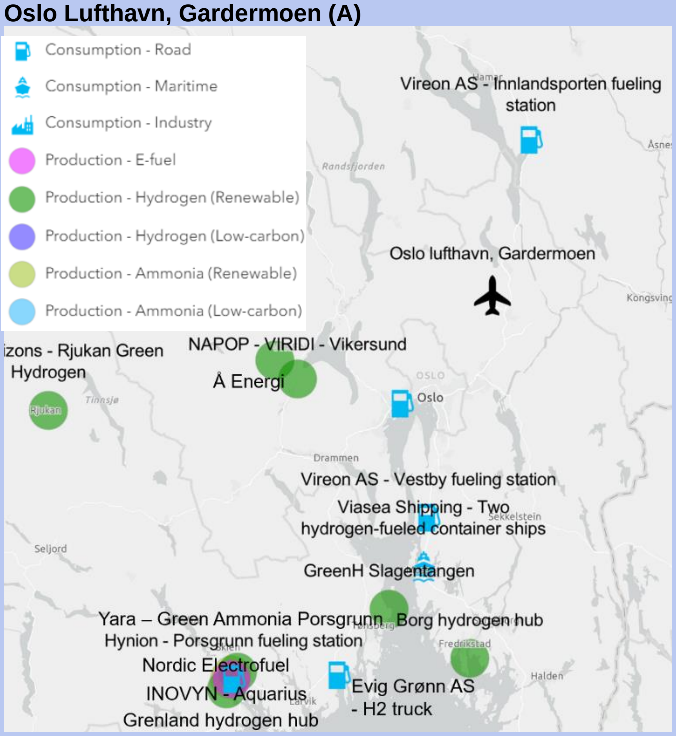
	Airport (category)	**Case 1** **Local H2 production**	**Case 2** **H2 pipeline transport**	**Case 3** **H2 Truck transport**	**Case 4** **H2 Ship transport**
A	Oslo, Gardermoen	[green]	[yellow]	[yellow]	[red]
B	Bergen, Flesland	[green]	[yellow]	[green]	[green]
	Stavanger, Sola	[green]	[yellow]	[green]	[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]	[yellow]	[green]
	Harstad-Narvik, Evenes	[green]	[yellow]	[green]	[green]

Table 4-2 gives a closer view on each airport and projects that can be potential hydrogen suppliers, as well as a brief description of relevant logistics solutions.

Table 4-2: Potential hydrogen suppliers to airports

Airport (Airport category)	

Oslo Lufthavn, Gardermoen (A)



Potential hydrogen production nearby

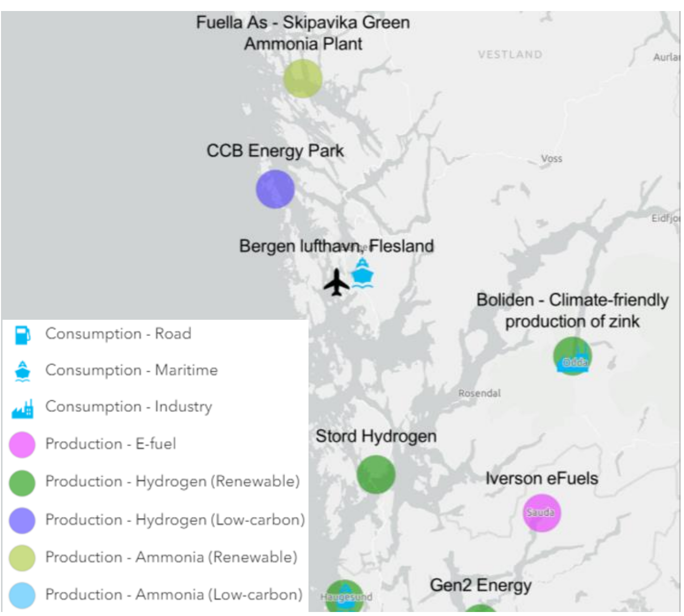
There are currently no large hydrogen projects close to Oslo Airport. There are some smaller initiatives close to Oslo on filling stations for heavy duty transport. There are two small-scale H2 production projects announced close to Vikersund (owned by Å Energi and NAPOP) (100 km).

The medium and larger-scale projects are located further away; Borg hydrogen hub (140 km), GreenH Slagentangen (150 km), and several announced projects at the industrial area at Herøya in Porsgrunn (210 km), including ammonia and e-fuels projects.

Possible logistics solution

Volumes from the announced projects are possible to transport by tube trailers or swap containers, but they are at the edge of viable transport distance and will add a significant cost element. Establishing an electrolyser closer to the airport with efficient swap container solutions or on site is likely a better business case.

Bergen, Flesland (B)



Potential hydrogen production nearby

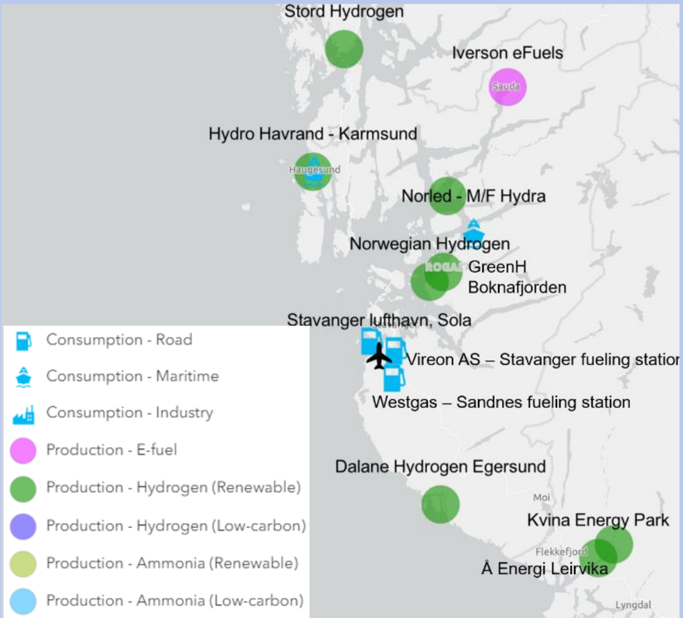
CCB Energy Park at Kollsnes (ZEG and CCB) (53 km): Plans for large scale low-carbon (blue) hydrogen production from fossil gas with CCS for maritime and road transport.

Stord Hydrogen (far by road when avoiding ferries): 1 MW plant (in operation from 2023) producing compressed hydrogen for road and maritime transport, construction and industry.

Possible logistics solution

The large-scale project planned at Kollsnes, and at Stord if it scales up, could potentially supply liquified hydrogen by ship to Flesland and other 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 and some industry sites could be relevant offtakers.

Stavanger, Sola (B)



Potential hydrogen production nearby

There are several announced projects in the area, the three closest ones are:

Norwegian Hydrogen, Tau industry park (40 km), 10 MW in 2025 and 30 MW in 2030

GreenH Boknafjorden (48 km): 6 MW in 2025

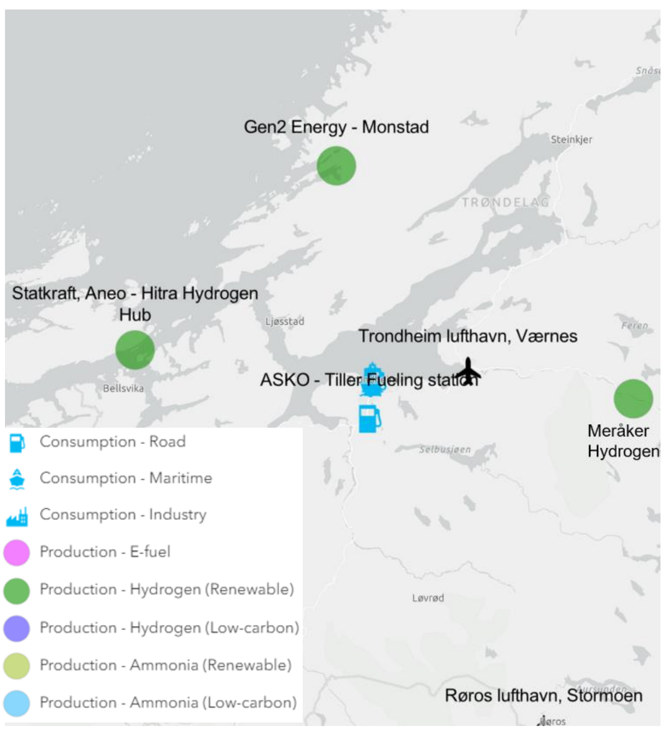
Dalane Hydrogen Egersund (73 km): 1 MW in 2024.

On hydrogen consumption there are several fueling stations for road transport planned in the area, and Nordled's Hydra ferry (Hjelmeland-Nesvig connection) is currently fuelled by liquid hydrogen from Germany. Future supply to these could also supply Sola.

Possible logistics solution

Hydrogen can potentially be transported by swap containers from the projects described above, however there can be challenges with long tunnel. Hydrogen can also be transported from other production facilities along the coast.

Trondheim, Værnes (B)



Potential hydrogen production nearby

There are no hydrogen projects in the immediate vicinity of Værnes. The closest is Meråker hydrogen (50 km), planning hydrogen production capacity of 10 MW in 2025 and 20 MW in 2030.

Hitra Hydrogen Hub (150 km) was granted funding from Enova in 2022 as 1 of 5 maritime hydrogen hubs, 10 MW planned in 2025 and 30 MW in 2030.

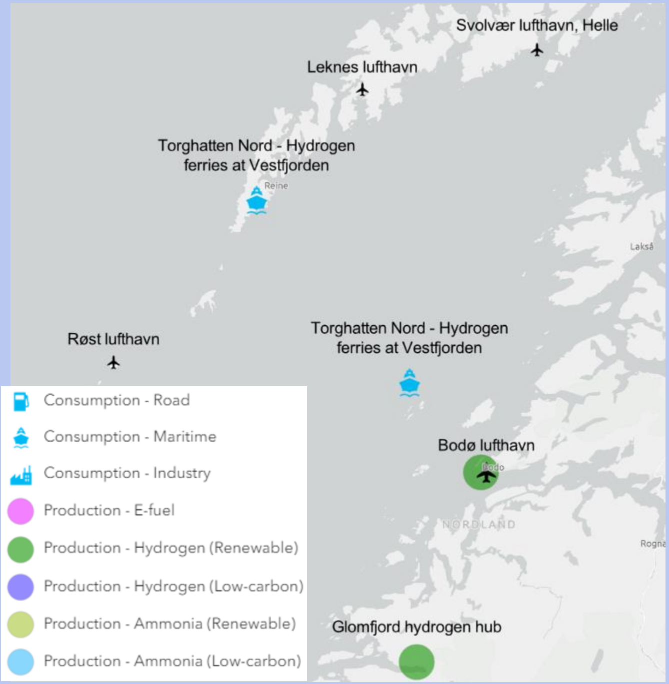
Gen2Energy plans large scale hydrogen production at Monstad (186 km).

Hydrogen fueling stations are planned in and around Trondheim.

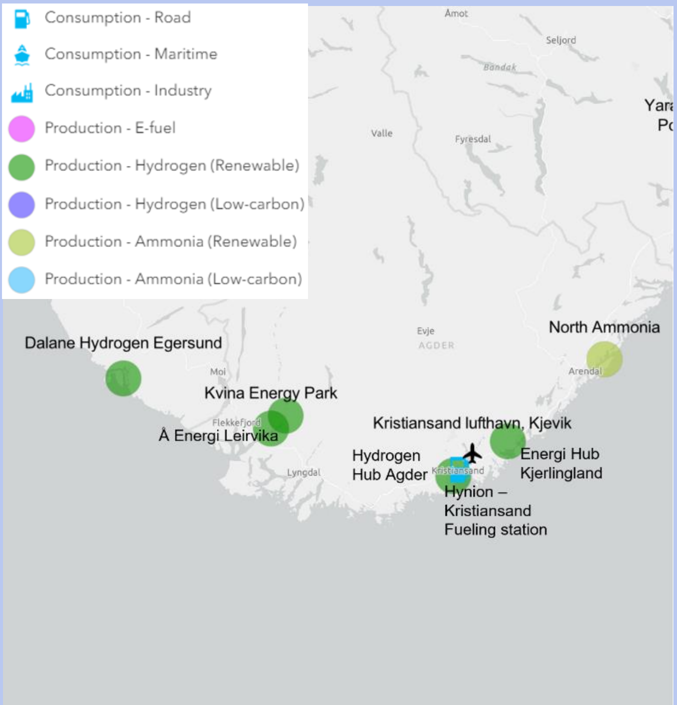
Possible logistics solution

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
 	The Vestfjorden ferries (Bodø-Lofoten islands) will be hydrogen driven from 2025. They have signed an agreement with GreenH Bodø to supply compressed hydrogen to the ferries from their planned production facility in Bodø (1km from airport). Glomfjord Hydrogen Hub (136 km) could also be a potential supplier. **Possible logistics solution** A good option would be pipeline or swap containers from GreenH Bodø. Possibilities also include hydrogen transported by ship as LH2 or ammonia depending on the local production prices and capacity (which is highly dependent on grid capacity). Transport of hydrogen with truck from Glomfjord might be possible.
Tromsø, Langnes (C)  	**Potential hydrogen production nearby** There is one project close to Tromsø lufthavn (20 km), but with ammonia as main planned end product: Neptun Tromsø AS (Troms Kraft, Magnora, Prime Capital) plans large scale renewable ammonia production of 50-70 000 tonnes annually). Statkraft, Finnfjord and CRI are planning e-methanol production capacity of 100 000 tonnes/year at Finnfjord (160 km). According to NHF no pure hydrogen projects are planned around Tromsø. **Possible logistics solution** Decent conditions for truck swap containers from Neptun due to short driving distance, but uncertain whether all the hydrogen will go to ammonia production. Tromsø airport is located seaside, which means good conditions for LH2 or hydrogen carriers by ship.

Kristiansand, Kjevik (C)



Potential hydrogen production nearby

There are several hydrogen projects planned around Kristiansand:

Hydrogen Hub Agder (20 km) is one of the maritime hydrogen hubs chosen by Enova in 2022, with planned production capacity in first phase of 20 MW (2024).

Energi Hub Kjerlingland (25 km) looks at possibilties for hydrogen production from solar and wind power.

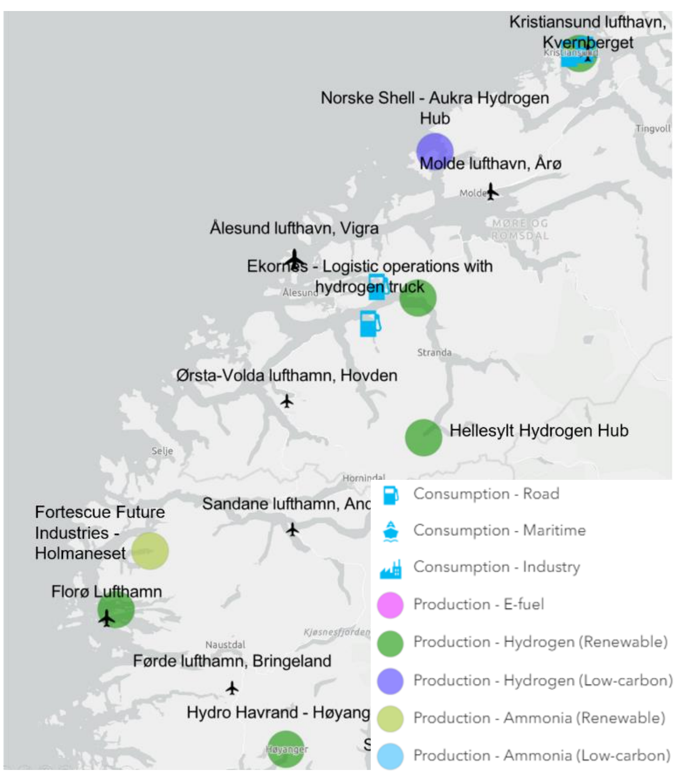
North Ammonia Arendal (66 km) plans large scale renewable ammonia production for maritime transport and export to Europe.

Kvina Energy Park (110km) plans large-scale production of hydrogen and ammonia.

Possible logistics solution

Good location for truck transport from the closest hydrogen hubs.

Åesund, Vigra (C)



Potential hydrogen production nearby

No projects in immediate proximity, but the airport is located shoreside.

The closest project, FjordH2 (63 km) is a joint development of Provaris Energy and Norwegian Hydrogen, planning large scale hydrogen production in Ørskog, with full capacity of 270 MW/40 000 tonnes per year.

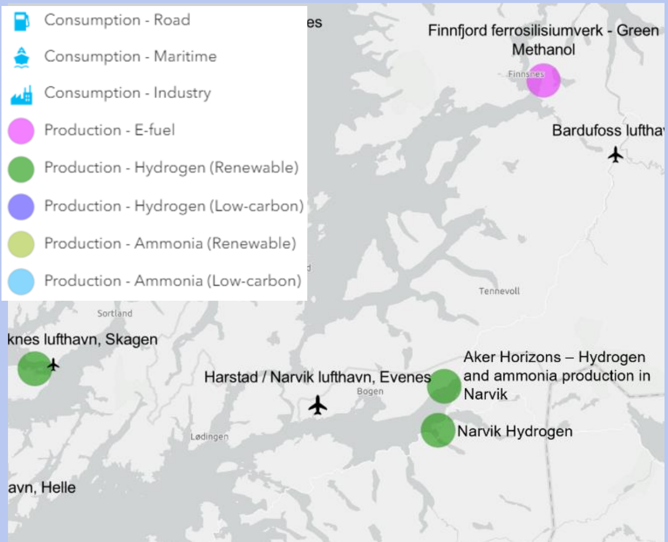
At Aukra, Aker Horizons, Norske Shell and CapeOmega plans production of 440 000 tonnes low-carbon (blue) hydrogen per year by 2030.

Hellesylt Hydrogen Hub plans 3 MW hydrogen production with operation start in 2024 (currently under construction).

Aukra and Hellesylt are relatively close in distance, but road transport requires ferry crossings.

Possible logistics solution

Potential hydrogen deliveries by ship from Aukra or by truck from FjordH2.

Harstad-Narvik, Evenes (C)	Potential hydrogen production nearby
	Aker Horizons (40 km) are planning large-scale production of hydrogen and ammonia in Narvik for maritime consumption and export to industrial consumers in Europe, with planned production capacity of 300 MW and estimated start-up in 2028 Norwegian hydrogen's project Narvik hydrogen (60 km) is a 10 MW hydrogen plant with estimated start up in 2025 **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. CCB and ZEG Power's project for low-carbon hydrogen at CCB Energy Park has received 77 MNOK from Enova.

Furthermore, in 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. The project is part of Hardanger Hydrogen Hub.
- Horisont Energi AS will through the Barents Blue project establish ammonia production from fossil 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.

In June 2022, Enova announced who was granted support under their funding scheme for maritime hydrogen hubs, supporting 5 production projects for renewable hydrogen along the Norwegian coast with 669 MNOK: Glomfjord, Rørvik, Hitra, Florø and Kristiansand (Hydrogenknutepunkt Agder). In addition 431,3 MNOK was awarded to 7 hydrogen and ammonia driven ships. In September 2023, Enova granted support to several maritime companies to acquire and build hydrogen- and ammonia powered ships and bunkering solutions.

Norwegian projects can receive grants from the EU Innovation fund, and in 2023 Fortescue Future Industries was granted around 200 MEUR, for their Holmaneset green ammonia project, and Nordic Electrofuel was granted around 40 MEUR for their e-fuels project. As mentioned in the introduction, projects in Norway can participate in the European hydrogen auction (which is also under the EU Innovation fund), where a pilot auction opened 23 November 2023 and will close 8 February 2024, and a second auction will open in spring 2024. The projects first have to pass on maturity criteria, before being ranked based on bid price. Awarded projects will get support in EUR/kg renewable hydrogen produced.

4.3 Overview of current and planned projects

Table 4-3 shows an overview of some of the more advanced developed hydrogen (and ammonia) production projects in Norway. The projects are sorted and selected based on planned production start according to the database from NHF

(Norwegian Hydrogen Forum, 2023)[2]. All these projects are planning renewable, i.e. electrolysis-based, hydrogen/ammonia, except for CCB Energy park producing low-carbon hydrogen from gas with CCS (first phase in operation from October 2023). Stord Hydrogen (1 MW) is already in operation from 2023, and Yara's green ammonia plant in Porsgrunn planned production start in 2023[3]. Although many of these projects have announced planned production start already in 2024 or 2025 most of them have not taken final investment decision, and 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 with planned production in the next few years (as of November 2023 ((Norwegian Hydrogen Forum, 2023)

Project name	Planned production start	Has FID been taken?	Planned initial capacity	Planned capacity 2030	Actors
CCB Energy Park (low-carbon H2)	2023	Yes (in operation)	1 tonne H2/day (2023), 20 tonnes H2/day (2025)	300 tonnes H2/day (2030)	CCB Energy, ZEG Power, H2 production
Stord Hydrogen	2023	Yes (in operation)	1 MW	1 MW	Stord Hydrogen AS, Hydrogen Solutions, Sustainable Energy Catapult, Alltc Services, Greenstat
Yara – Green Ammonia Porsgrunn	2023	Yes (under construction)	3650 tH2/year 20 500tNH3/year 24 MW	530 000 tNH3/year, approx. 95 000tH2/year	Yara, Linde
Hellesylt Hydrogen Hub	2024	Yes (under construction)	3 MW	3 MW	Norwegian Hydrogen, Hexagon Purus, Hyon, Tafjord, Sintef, Gexcon, Stranda Energi, Stranda Kommune, Innovasjon Norge, Forskningsrådet
Hardanger Hydrogen Hub	2024	No	2 MW	20 MW	Statkraft, Fluorsid, Tizir, TechnipFMC Kongsberg, Odda Technology, Hydrogenvegen, Kongsberg Innovasjon, GCE Ocean Technology,

[2] There are more projects with announced production start in 2025, for the table the larger ones above 10 MW were selected

[3] No public information that this is in production as of 22.12.2023

					Næringshagen i Ullensvang
Dalane Hydrogen Egersund	2024	Yes	1 MW	1 MW	Dalane Hydrogen, Hydrogen Solutions, Dalane Energi, Egersund Næring og Havn
Hydro Havrand – Høyanger	2024	No	5 MW	15 MW	Hydro Havrand, Hydro Høyanger
Hydrogen Hub Agder	2024	No	20 MW	60 MW	Everfuel, Greenstat
Hydrogen Hub Mo	2024	No	40 MW	300 MW	Statkraft, CELSA, Mo industripark
Green Ammonia Berlevåg	2024	No	100 MW	100 MW	Aker Horizons, UBFC, Cummins, Tecnalia, University of Sannio, Varanger Kraft, KES
GreenH Bodø	2025	No	15 MW	Unknown	GreenH
Glomfjord Hydrogen hub	2025	No	20 MW	20 MW	Nel, Greenstat, Meløy Energi, Troms Kraft.
Rjukan Green Hydrogen	2025	No	20 MW	40 MW	Aker Horizons
Norwegian Hydrogen Tau	2025	No	10 MW	30 MW	Norwegian Hydrogen
Grenland hydrogen hub	2025	No	20 MW	20 MW	Statkraft, Skagerak Energi
Meråker Hydrogen	2025	No	10 MW	20 MW	Meraker Hydrogen, Gen2 Energy, Aker Horizon, NTE, Greenstat
Hitra Hydrogen Hub	2025	No	10 MW	30 MW	Statkraft, Aneo
Rørvik Hydrogen Hub	2025	No	20 MW	20 MW	NTE and H2 Marine

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.

The newly adopted mandatory SAF blending mandates from 2025 will be the main driver of decarbonization in the European aviation sector going forward. However, hydrogen has the potential to play a key role in decarbonization of aviation – especially for medium-haul routes. 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. The main challenge for production projects to be realized is to secure offtake. New production is generally easier to scale than new offtake. 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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