SMØLA HYDROGEN VALUE CHAIN

PROJECT FOR MØRE AND ROMSDAL COUNTY COUNCIL (NORWAY), WITH SUPPORT BY INTERREG NORTH SEA REGION

Interreg
North Sea Region
G-PaTRA
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Møre og Romsdal
fylkeskommune

REPORT

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J C G C
CONSULT

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ABBREVIATIONS

BE	Battery-electric
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
FC	Fuel Cell
FCE	Fuel Cell Electric
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
GT	Gross Tonnage
H_2	Hydrogen
kg	kilogram
kn	knot (1 kn = 1.85 km/hr)
kWh	kiloWatt hour (1 kWh = 3.6 MJ)
LCA	Life Cycle Analysis
LHV	Lower Heating Value
MJ	Megajoule
MNOK	Million NOK
MW	Megawatt
NEAS	Nordmøre Energiverk AS
nm	Nautical mile
NMVOC	Non-methane Volatile Organic Compounds
NOK	Norwegian Kroner (1 NOK = ca. 0.10 €)
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditures
SMR	Steam Methane Reforming
TCO	Total Cost of Ownership
VAT	Value Added Tax

EXECUTIVE SUMMARY

Smøla is an island community located in the Møre & Romsdal county, north-west in Norway. Through foresight, ambition and close collaboration between public and private entities, Smøla has established itself as a pioneer in onshore wind power, with 68 turbines and 150 MW generation capacity. The wind farm came into operation in the early 2000s, bringing value to the local community as well as paving the way for other large-scale onshore wind power projects in Norway at Fosen, Hitra and Snillfjord.

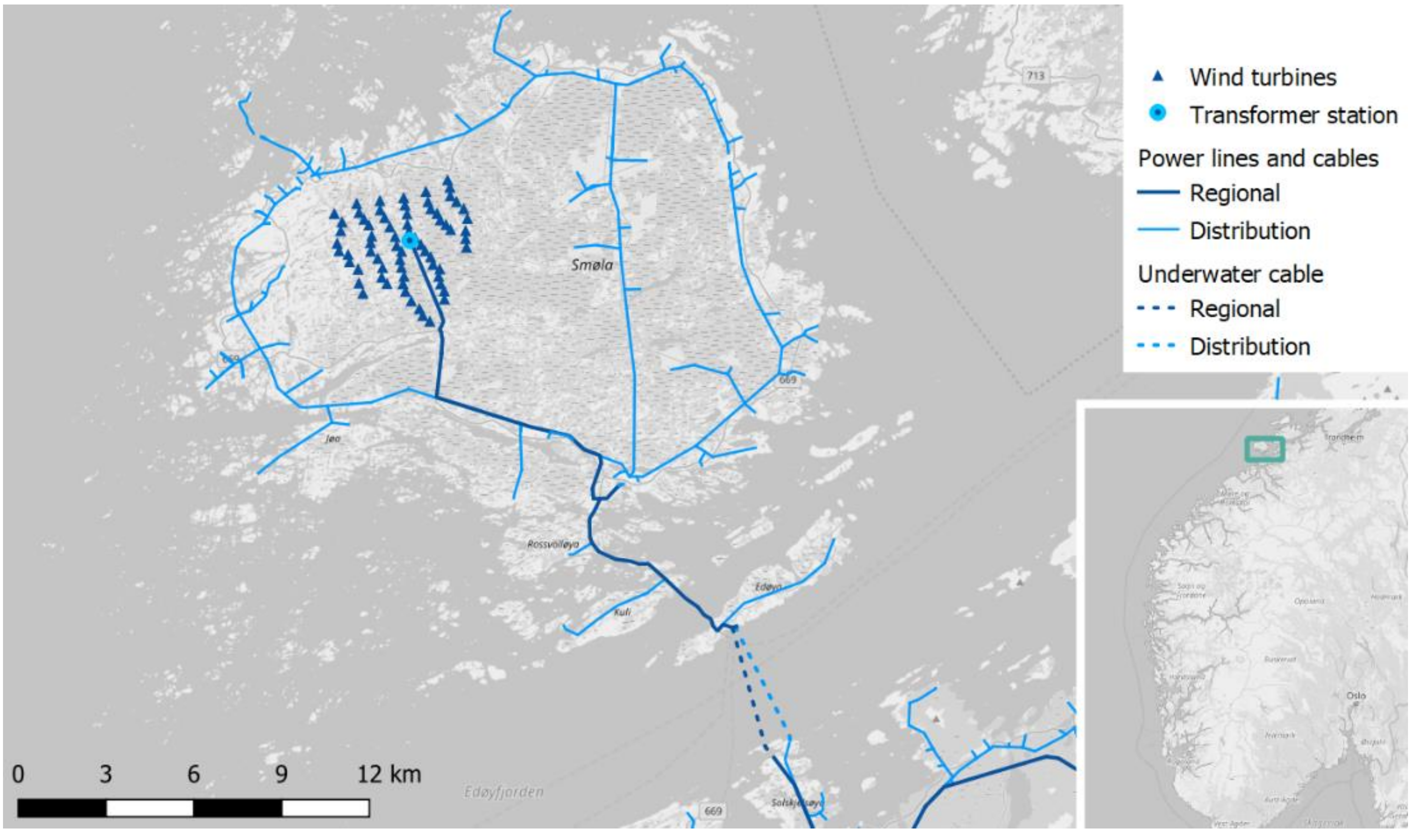

Figure 1 - Project location, wind park and power lines on Smøla

Smøla municipality is now evaluating how their leading position in wind power can give them an upper hand in other renewable energy sectors. The power cable between Smøla and the mainland has effectively reached its capacity, preventing additional capacity expansions of the turbines. A new export power cable from the island to shore is considered too expensive. Meanwhile, Smøla also aims to reduce their greenhouse gas emissions from transport, of which the high speed ferry and buses constitute a significant share.

Previous studies from amongst others Greensight and the Norwegian National Wind Energy Centre show that locally produced hydrogen present significant advantages both for local value creation and for reducing greenhouse gas emissions from transport.

Endrava, in collaboration with Hyon and JC Gjerløw Consult, have been asked to perform a techno-economic study of possible hydrogen value chain concepts, all based around the production of hydrogen from Smøla's wind farm. This report aims to answer the following question:

Should hydrogen be produced at Smøla?

Our analysis shows that, with some reservations, the answer is yes. We base this analysis on three main reasons:

1. From a demand perspective, significant and predictable consumers technically eligible for conversion to hydrogen exist at Smøla. High speed ferries and local busses can together account for more than 1,000 kg of hydrogen demand, daily. It is also expected that in a regional context, the demand side for hydrogen will increase in the years to come of which Smøla may provide part of the supply.

2. From a supply perspective, the hydrogen value chain at Smøla can be made competitive with production costs ranging from 27 to 47.3 NOK/kg. Hydrogen in Norway for transport is currently retailed at around 72 kr/kg (ex. VAT), leaving a potentially significant profit margin.

3. From an environmental and safety perspective, hydrogen from renewable energy is well positioned to replace diesel with corresponding strong emission reduction potential. Hydrogen production, filling stations and bus applications are already mature technologies, in accordance with industry norms for safety standards. For maritime applications, a strong development race is on-going, giving confidence that compliance with safety standards are around the corner.

This structure of this report mirrors the main reasons above. Appendixes A to D detail the method, background data and sources.

The project team makes several recommendations for further work:

- First, efforts should be made to coordinate timing of supply and demand. High speed ferries is key for a significant, stable and predictable base load. To drive development, the county administration should consider specifically demanding hydrogen for the next high speed ferry contract. Buses could provide an additional stable load. However, bus procurement would only make sense if part of a bigger regional initiative since there are only two buses at Smøla. The county administration could have a coordinating role for such an initiative on buses.
- Second, electricity costs is by large the main driver in achieving competitive hydrogen costs and favorable project economics (see section C3.2 Sensitivity analysis). Dialogue with the local power producer Statkraft and grid operator NEAS to achieve predictable, low energy costs will be essential for the project.
- Finally, investment grants do help reduce the break-even price for hydrogen production (see section C3.4 Investment support). The project should therefore seize the opportunity to apply for support along the different project phases, starting with Pilot-E funding immediately, since the deadline for the call for proposals in 2019 is September 25th.

Note that the scope of this project is limited to assessing possible hydrogen value chain concepts for Smøla, and does not compare the applicability of hydrogen with other low or no-emissions technologies.

1 DEMAND SIDE

From a demand perspective, significant and predictable consumers technically eligible for conversion to hydrogen exist at Smøla. High speed ferries and local busses can together account for more than 1,000 kg of hydrogen demand, daily. It is also expected that in a regional context, the demand side for hydrogen will increase in the years to come of which Smøla may provide part of the supply.

1.1 USERS ARE BECOMING MORE MATURE TECHNOLOGICALLY

Most users are becoming increasingly mature as technologies are developed and projects gets carried-out. However, the technological maturity of hydrogen users varies across sectors and vehicle segments. The descriptions below focus on the most relevant users for Smøla.

1.1.1 HIGH SPEED FERRIES

The interest for use of hydrogen in the maritime sector has increased significantly the last years. Fossil-free maritime operations and the possibility of new business opportunities for a traditional Norwegian industry is a good combination. Clusters like NCE Maritime CleanTech and Ocean Hyway Cluster have helped increase the attention at shipyards. We now see several projects for the use of hydrogen as fuel for maritime applications maturing, including passenger and car ferries, service vessels for fish farming and others.

Hydrogen passenger ferries*

- 400 kg H_2 per way, 2.5 tonnes per day
- H_2 storage on board: 450 kg
- Bunkering: ca. 1 200 kg/h may be possible
- Bunkering required once every trip
- Hydrogen cost: 30-50 NOK/kg

** Source: MoZEES. Figures from the Trondheim-Kristiansund route*

Pilot-E is a joint governmental funding scheme for the Norwegian Research Council, Innovation Norway and Enova (Pilot-E). In 2018, four projects where granted funds for zero emission solutions for different vessels – two for high-speed passenger ferries, one for a hybrid battery-hydrogen solution for emission-free operation of the ordinary coastal routes for transport of goods, and one for transport of containers, helping moving goods from road to sea (Pilot-E, 2018).

Ferries represents a large amount of GHG emissions for most Norwegian counties. The Norwegian Public Roads Administration is responsible for some of the regional car ferry services and is a driving force for zero emission solutions as well. Siemens and Bellona have compiled a feasibility study for the electric drive of the Norwegian car ferry service (Bellona, 2015). The study estimates that with current technology it is profitable to replace a total of 127 of Norway's 180 ferries with either battery or hybrid operation. For the remaining 43 ferries, the study concludes that hybrid solutions should be used. For these, hydrogen is a possible solution.

Figure 2 - High-speed passenger ferry, planned for the Florø – Måløy route. Illustration: Brødrene Aa

1.1.2 BUSES

Hydrogen buses

- *Range: Ca. 300 km*
- *Consumption: 8.6 kg/100km (class 1), 10 kg/100km (class 2)*
- *Cost: TCO estimated 40% higher than diesel buses.*

Urban hydrogen buses are one of the most mature fuel cell and hydrogen applications. Several large-scale demonstration projects have tested the technology in Europe and led to high maturity levels. Costs have also been reduced significantly since the first prototypes were launched. There are different types of hydrogen buses, from buses with small batteries and a large fuel cell, to those with large batteries and a fuel cell as a range extender.

European projects like CHIC, JIVE 1 and JIVE 2 have deployed several hundred hydrogen buses in cities and regions in Europe. Late 2018, a hydrogen bus initiative from Nel Hydrogen, H2Bus Europe, achieved funding from CEF (Connecting Europe Facility) (NEL, 2018). H2Bus Europe will deploy 600 FC Buses in Denmark, Latvia and the UK. Ruter, the public transport company in Oslo and Akershus, has been operating 5 hydrogen buses since 2012 as part of the CHIC project (CHIC, 2016). Ruter is now participating in JIVE 2 aiming to have 10 more hydrogen buses on the road (JIVE 2, 2019). The hydrogen bus tender will be integrated into a larger bus services tender. Ruter has achieved funding from JIVE (14 MNOK) and Enova (38 MNOK) for the project

While urban buses (class 1) can be delivered by several manufacturers, regional buses (class 2) are still difficult to acquire. Ruter was aiming for using hydrogen class 2 buses for their services in Akershus west. Two OEMs offered class 2 buses, but the infrastructure was more expensive than estimated. At the time of writing it is uncertain whether the project will be implemented. Ruter seems to rely on Battery Electric buses for the urban routes, while hydrogen buses are considered necessary for the regional routes to be emission free. For public transport in Norway to become zero emission, the availability of class 2 hydrogen buses is thus important, and it is expected that Ruter's project can help making the buses available.

Figure 3 - Ruter has since 2012 had 5 hydrogen buses in operation in Oslo and Akershus. Photo: Ruter AS / Redink: Krister Sørbø

1.1.3 OTHER TRANSPORTS

Applications for hydrogen as a fuel are being developed across other transport segments. These segments are not expected to represent a significant role for the hydrogen demand at Smøla in the short term, and only a summary is provided in this section. Refer to *Appendix A - Users description* for a more detailed description.

The market for fuel cell light duty vehicles is limited at the moment, with only two models available in Norway: only Toyota and Hyundai offer FCEVs in the country. One of the biggest obstacles for an accelerated European market uptake is the current lack of availability of commercial products from OEMs (Roland Berger, 2018). In terms of adoption, there were 28 new registrations of FCEVs in Norway from January - May 2019, making a total of 176 registrations per May 2019 (NHF / OFV, 2019).

With regards to heavy duty vehicles, only initial prototypes have been developed so far and larger-scale roll-out is yet to begin. That said, many interesting things are going on within this segment. Scania will deliver the first 4 hydrogen trucks to the Norwegian food wholesaler ASKO in 2019 (ASKO, 2019). However, there are no indications from Scania that they will continue development and manufacturing of FC trucks. Hyundai Trucks is to deliver 1,000 FC trucks in Switzerland within 2023, and a total of 1,600 within 2025. In April 2019 Nikola presented several models, including the Nikola Tre dedicated to the European market. Testing is scheduled to start in Norway together with Nel in 2020, with mass production from 2022-2023.

Hydrogen trains seem to be the only viable zero-emission alternative for regional train services operating on non-electrified lines. The world's two first hydrogen passenger trains have since September 2018 been part of the commercial service in Lower Saxony, Germany. The Coradia iLint is developed by Alstom, one of Europe’s largest railway manufacturers. LVNG, the organization responsible for public transportation in Lower Saxony, has already ordered a further 14 hydrogen trains from Alstom, which are scheduled to start driving this route within the next two years, and is considering replacing its entire 126-train fleet with hydrogen-powered locomotives (Expat, 2019). According to Alstom, several other countries are also looking into hydrogen trains, including Britain, the Netherlands, Denmark, Norway, Italy and Canada.

Within the maritime sector, other segments than passenger vessels are also starting to implement fuel cells. Projects with fishing vessels are underway, for example in Norway, France and Japan (TU, 2017, Mer et Marine 2018, Safety4Sea 2019), and a design exists for a fish farm service vessel (NVE, 2017). Hydrogen could also be used as a fuel to produce electricity and oxygen for coastal fish farms (iLaks.no, 2018). Samskip is leading a project to develop two hydrogen-fueled container ships, and received Pilot-E funding for the project (Samskip, 2018). A techno-economic study from DNV GL (2018) shows however that hydrogen is best suited for passenger ships below 9,999 gross tonnage within a 2030 horizon. The future roll-out of hydrogen in other ship segments is therefore uncertain at the moment.

1.2 USERS REPRESENT SIGNIFICANT HYDROGEN VOLUMES

1.2.1 HIGH SPEED FERRIES

If converted to hydrogen, the high speed ferries on the line Trondheim - Brekstad - Kristiansund could need up to 1.15 tonnes$_{H2}$/day at Edøy (see also demand analysis in appendix C). This demand is expected to be stable and foreseeable through the year, which is a big advantage for the business case of hydrogen production.

The Trondheim - Brekstad - Kristiansund line is illustrated on the map below.

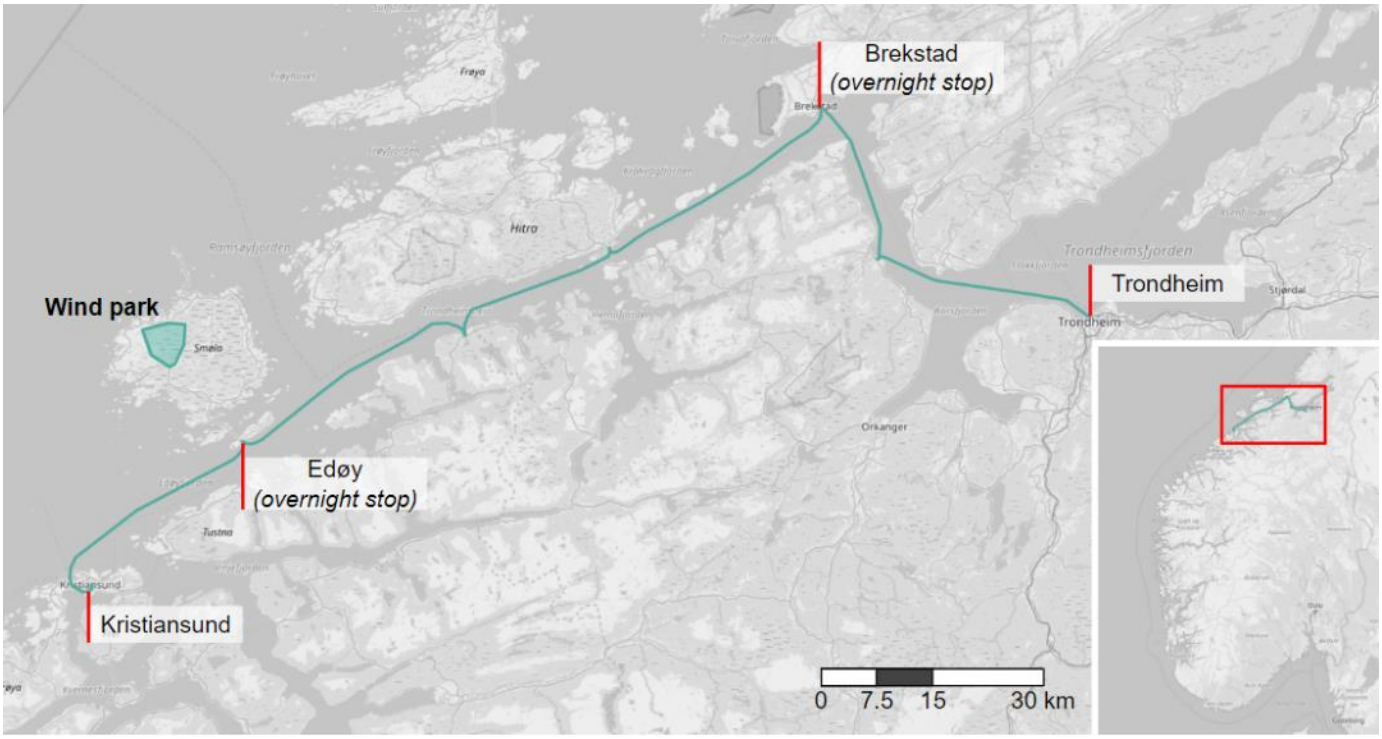

Figure 4 - High speed ferry line Trondheim - Brekstad - Kristiansund. Source: Endrava

Endrava carried-out a simulation of the hydrogen consumption along the Trondheim - Brekstad - Kristiansund line, and of the filling time and hydrogen tank levels (appendix C). The results show that hydrogen bunkering at Edøy and at Trondheim is enough to allow sufficient tank levels throughout the service, with a safety margin. This would require only minor adjustments to the existing time table, and bunkering time at Edøy could be optimized to minimize disruptions during rush-hours.

Based on the current fuel consumption on the line, it was estimated that a total of 1,155 kg$_{H2}$ would be bunkered at Edøy each day, and 1,294 kg$_{H2}$ at Trondheim. Due to design constraints, it is assumed that the existing high speed ferries will not be converted to hydrogen, and that newbuilds would be needed instead. This would also be an opportunity to optimize the boat design, and it could allow for energy savings compared to the existing ones. With a new boat design, the project team assumed that the energy use could be reduced by 30%. This opens for the possibility to reduce the bunkering volume and time in Edøy, in order to minimize the disruptions to the existing time table. In that case, only 512 kg$_{H2}$ would be bunkered at Edøy, and 1,202 kg$_{H2}$ at Trondheim, each day.

Service is reduced on weekends, and the yearly consumption was estimated to 781 tonnes$_{H2}$ with the current fuel consumption, of which 368 tonnes$_{H2}$ would be bunkered at Edøy. In case of higher energy efficiency, the demand could be 547 tonnes$_{H2}$ per year, including 163 tonnes$_{H2}$ bunkered at Edøy.

The existing contract for the ferries will last until 2024 (Kollektivtrafikkforeningen, 2018), and the hydrogen demand from high speed ferries at Smøla/Edøy could therefore start that year, as illustrated below.

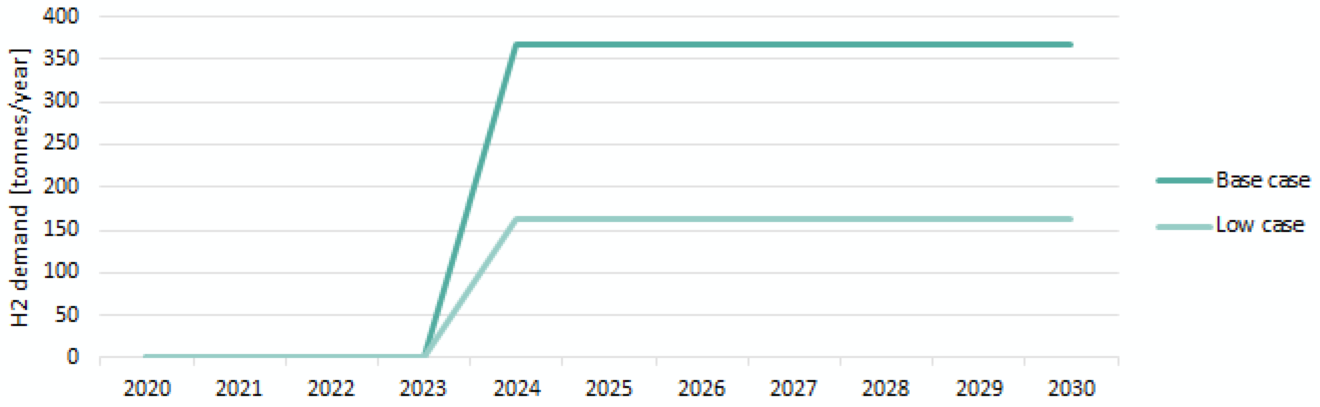

Figure 5 - Potential hydrogen demand from high speed ferries at Smøla / Edøy

1.2.2 BUSES

The two buses operating on Smøla would consume ca. 19 tonnes$_{H2}$/year (appendix C), which would be a stable complement to the demand from the high speed ferries.

The buses are operated by Tide Buss AS, and the current contract expires January 2024, with an option for one more year (Kollektivtrafikkforeningen, 2019). The figure below illustrates the potential hydrogen demand from buses at Smøla. The low case corresponds to the extension of the current contract for one year.

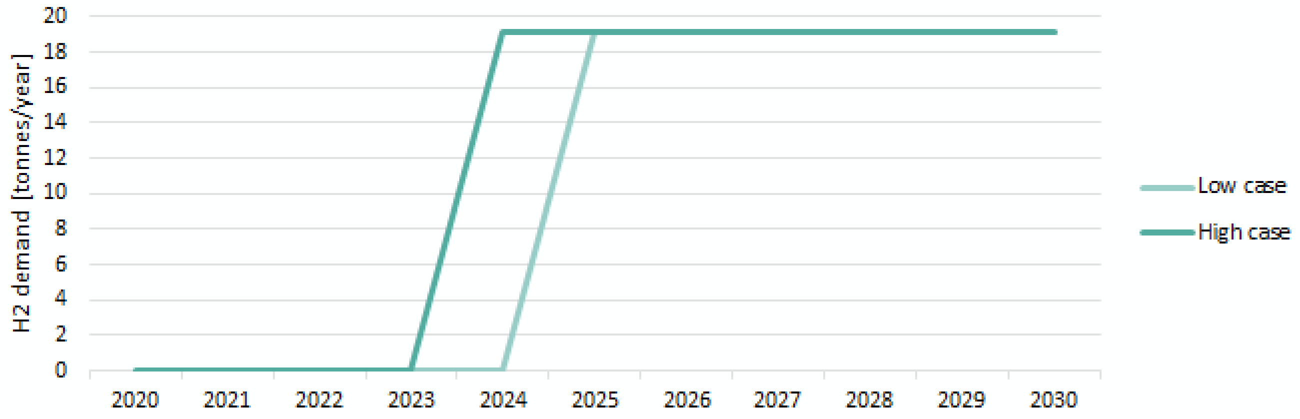

Figure 6 - Potential hydrogen demand from buses at Smøla

1.2.3 OTHER USERS

The adoption of hydrogen personal vehicles is merely starting in Norway and it is challenging to assess the future demand from these vehicles. Endrava estimated the potential demand to reach 3.1 to 6.3 tonnes$_{H2}$/year at Smøla by 2030, with large uncertainties.

Very few heavy-duty vehicles drive at Smøla, and trucks are therefore expected to make a very small contribution to the potential local hydrogen consumption. The ambulance boat MS Øyvakt has special requirements in terms of fuel capacity and speed, and it is therefore unlikely that it could be converted to hydrogen with its current design.

Smøla could also provide hydrogen to consumers in the rest of the county, depending on their location and the price-point for the hydrogen. The assessment in appendix B shows a potential total hydrogen demand between 1,546 tonnes$_{H2}$/year for the low case, and 3,473 tonnes$_{H2}$/year for the high case, as illustrated below.

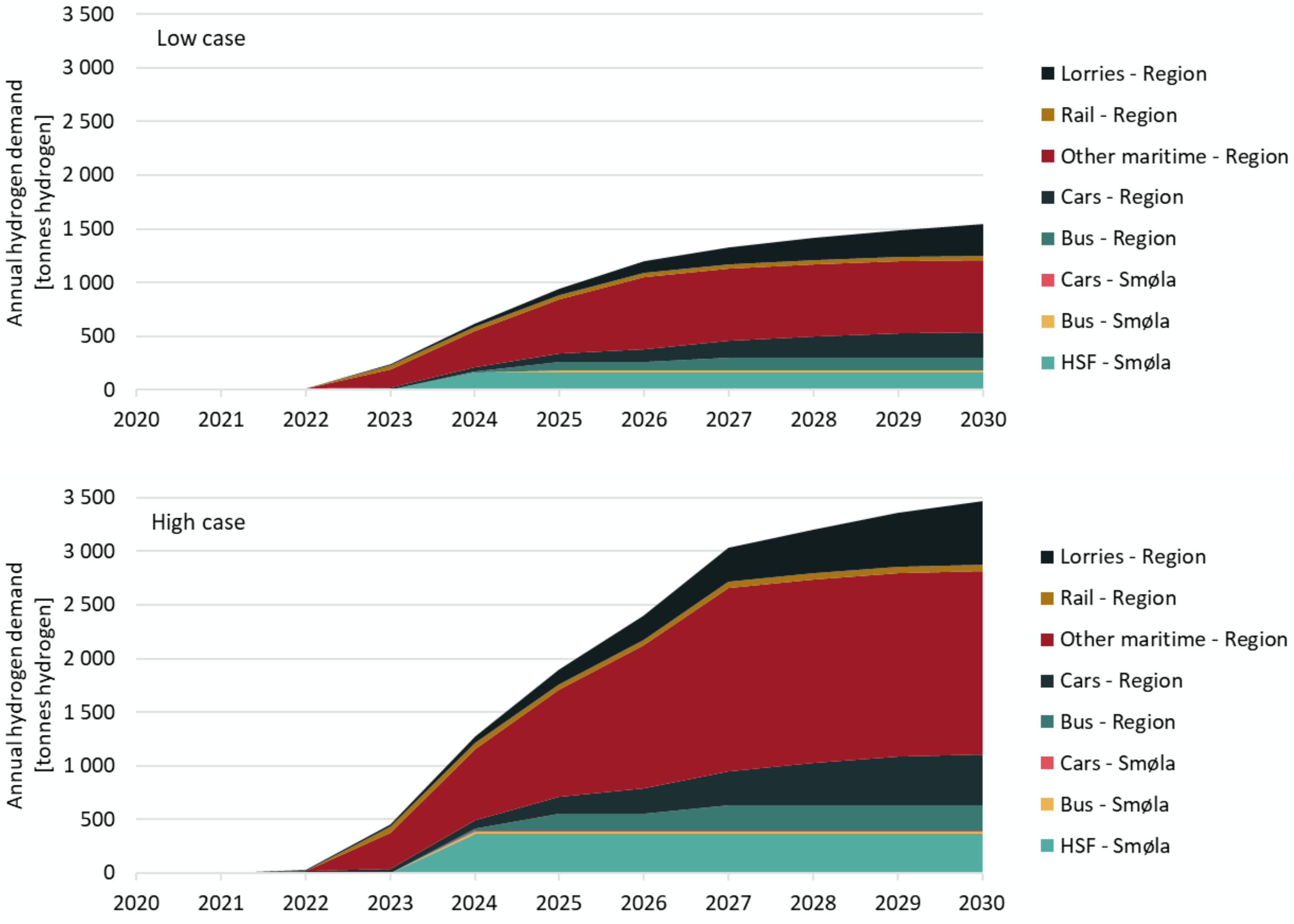

Figure 7 - Evolution of the estimated hydrogen demand in Møre and Romsdal until 2030. Top: low case. Bottom: high case

When focusing on Smøla, no demand is expected before 2024. It is clear that the high speed ferries make most of the hydrogen demand already in 2025 (high case), and still in 2030. For the rest of the county, there is very little demand by 2022, and the maritime sector make most of the demand in 2030, as illustrated in the figure below (note the difference in scale with the figure above). The future implementation of hydrogen as a fuel to the maritime sector is however uncertain.

Demand located in a radius up to Molde and Åndalsnes is considered relevant for this project. This includes Kristiansund, but does not include potential demand in the neighboring county, Trøndelag. This is partly due to scope limitations with a focus on the Møre og Romsdal county and partly since it is likely that Trøndelag will develop its own hydrogen infrastructure.

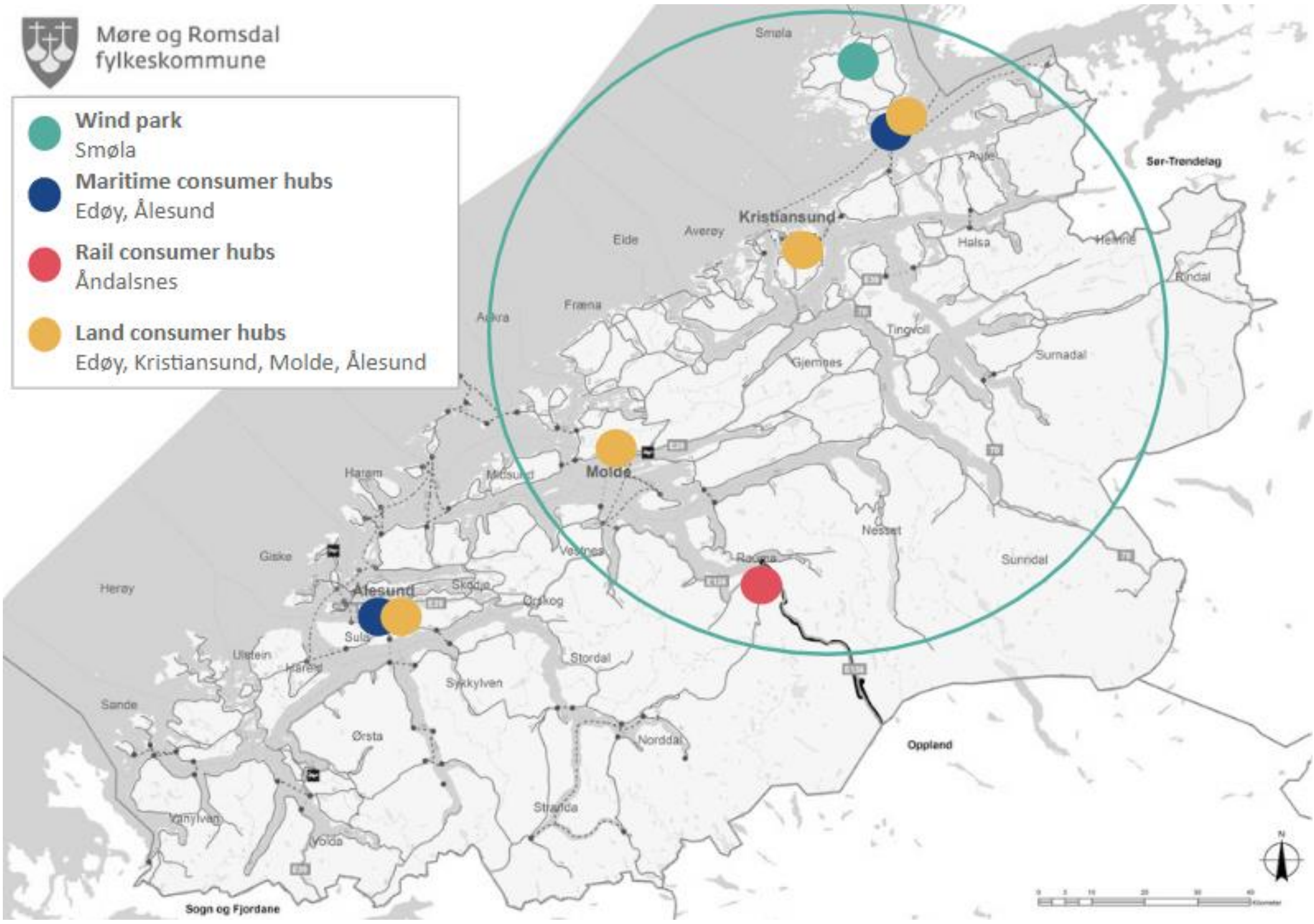

Figure 8 - Location of the main consumer hubs in the county, and radius for the relevant demand for this project (green circle)

1.3 USERS ARE BECOMING MORE COMPETITIVE ECONOMICALLY

1.3.1 HIGH SPEED FERRY

The county of Trøndelag has a tender for a hydrogen passenger ferry, where five consortia are working on different high speed ferry concepts, some with hydrogen. In MoZEES, the research center for zero emission transport systems, the institutes and the industry is also studying the high speed ferry case; working together on several topics that need clarification and evaluation. Examples are load profiles, hydrogen specific solutions and systems, authority approval, risk analysis and techno-economic studies. The Trondheim – Kristiansund route has been studied by MoZEES, taking a concept of Brødrene Aa as a basis. There are still several issues to be solved, related to: bunkering, storage capacity on board, fuel cell systems, etc. An article regarding risk assessment of a hydrogen fueled high speed passenger ferry was recently published as part of a maritime case study conducted within FME MoZEES (MoZEES, 2019). The conclusion of the study is that risks associated with the hydrogen systems on the ferry are well within expected tolerance criteria.

Since hydrogen high speed ferries are still at the design stage, there is currently very little information available on the competitiveness of these vessels compared to what is available for land transport (buses and cars). From an investment perspective, the additional CAPEX for high speed ferries is expected to be ca. 20 MNOK per vessel (estimate by HYON). DNV GL (2018) indicates an additional CAPEX of ca. 30 MNOK in 2021, with a reduction to 16 MNOK in 2030 for passenger vessels below 1,000 GT (the current high speed ferries have 492 GT). This increase in CAPEX compared to conventional vessels is mainly due to the cost of fuel cells, hydrogen tanks and batteries (HYON, DNV GL 2018). HR Prosjekt (2017) studied hydrogen concepts for two routes in the fjord of Oslo, and evaluated the CAPEX to be ca. 60% higher for hydrogen ferries than for diesel equivalents. The CAPEX of high speed hydrogen ferries may be reduced through public support, e.g. the Norwegian NO_X fund.

As to additional OPEX for hydrogen fueled high speed vessels, some general issues are discussed in the following. The price of hydrogen is expected to have the single most influence on operational expenditures, depending on the price point and the energy consumption of the vessel. Other technical operating costs involving fuel cells will be dominated by the life time of maritime fuel cells. It must be noted that the life time will be radically longer than automotive applications, owing to much less load dynamics. Typically, maritime applications will see life times of 30,000 hours before the cell stack will need replacement. The replacement of the stacks could typically amount to ⅓ of the initial capex. The main cost driver for the fuel cell maintenance costs is therefore linked to the cell stack replacement, the need for special competence and for safety precautions when doing maintenance on the equipment. Very little routine maintenance is however expected, since there are few moving parts. For the early movers, it is likely that special precautions, including extra follow-up and supplier monitoring, will have a cost penalty. HR Prosjekt (2017) evaluated the OPEX to be ca. 40% to 75% higher with hydrogen ferries compared to conventional diesel ones. Part of the increase is linked to increased hydrogen costs in the Oslo fjord pre-project.

1.3.2 BUS

Roland Berger (2017) estimates that the TCO of hydrogen buses is currently 30 to 40% higher than for diesel buses, as shown in Figure 9 below. The potential in the long term is a TCO that is 5 to 10% higher. This is based on a large-scale production of FC buses. The TCO is partly dependent on the fuel costs, which would be dependent on the hydrogen production costs in the case of Smøla.

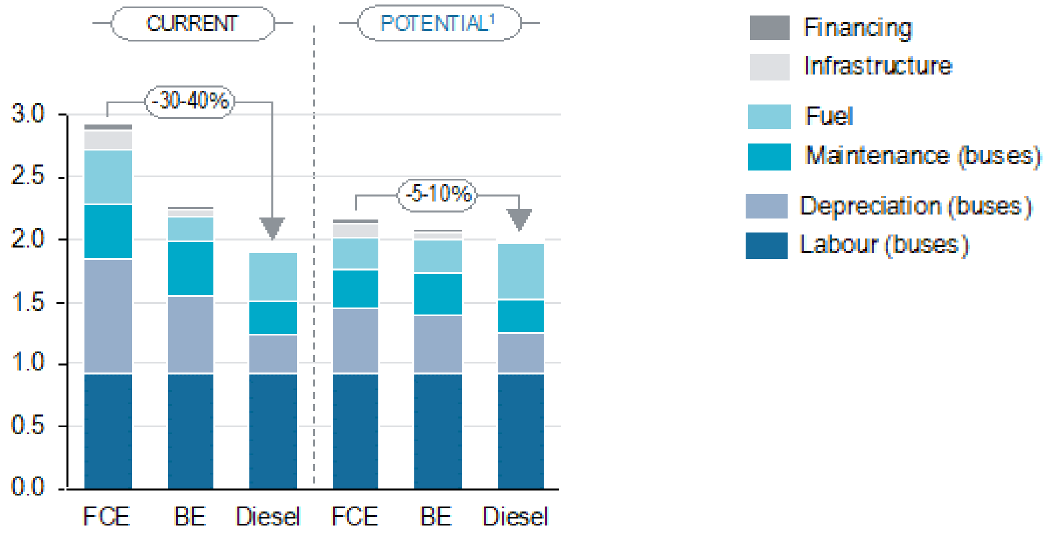

Figure 9 - TCO annualized at 2017 prices for fuel cell (FCE), battery-electric (BE) and conventional diesel buses, in €/km. The "potential" scenario requires a number of FC-related and other factors to fall into place in the medium/long run (Roland Berger, 2017)

Economies of scale are important for hydrogen fuel cell buses. A minimum amount of buses is required to get attention from bus manufacturers. Especially if adjustment to standard specifications of the bus are needed. The cost per bus will depend on the size of the order. Similarly, maintenance and infrastructure costs are dependent on the size of the bus fleet.

Only 2 buses are operating at Smøla. For this reason, a hydrogen bus project at Smøla would have more chances of success if it is coordinated with other projects in the region. A coordinated demand could allow attracting attention from bus manufacturers, and allow for economies of scale.

2 SUPPLY SIDE

Endrava studied two cases for hydrogen production at Smøla. Both cases are deemed technically and economically feasible, and produce enough hydrogen to supply the high speed ferries and the buses on Smøla. Case A groups the production and distribution at Edøy (site 1 on the map below), while case B has production at Vikan (site 2), and distribution at Edøy and Vikan, including capability to deliver hydrogen to other locations in the region, by truck.

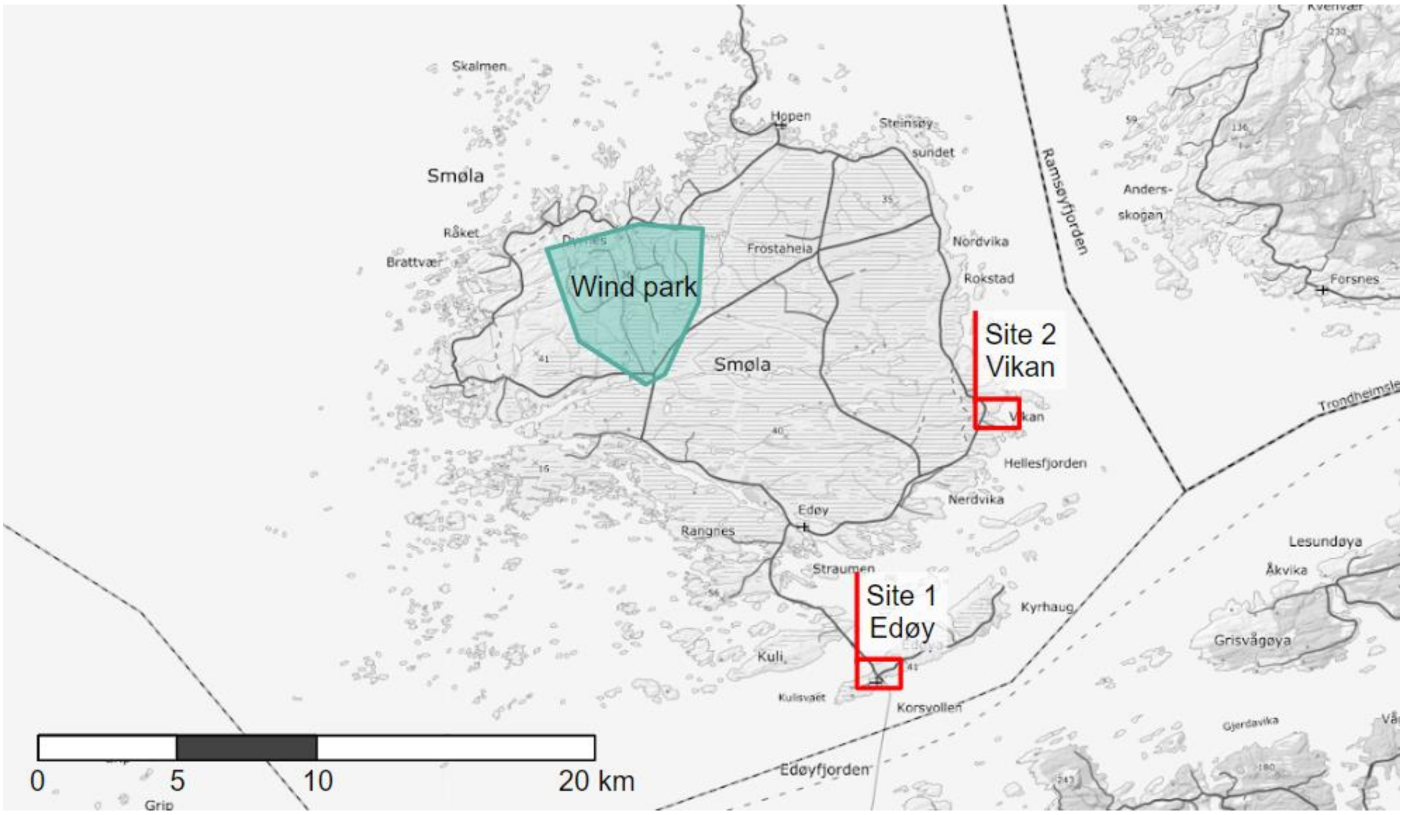

Figure 10 - Location of the two sites for production and distribution of hydrogen, and of the wind park at Smøla

2.1 OUR CONCEPTS PROVIDE COMPETITIVE PRODUCTION COSTS

Both case A and case B provide competitive hydrogen production costs when compared to average retail prices to the transport sector in the country, and to other similar projects in Norway.

The figure below shows a comparison of the production cost at Smøla with the current retail price for hydrogen in Norway (ex. VAT) and for an equivalent in diesel, taking into account energy content and typical efficiencies for hydrogen fuel cells and diesel engines.

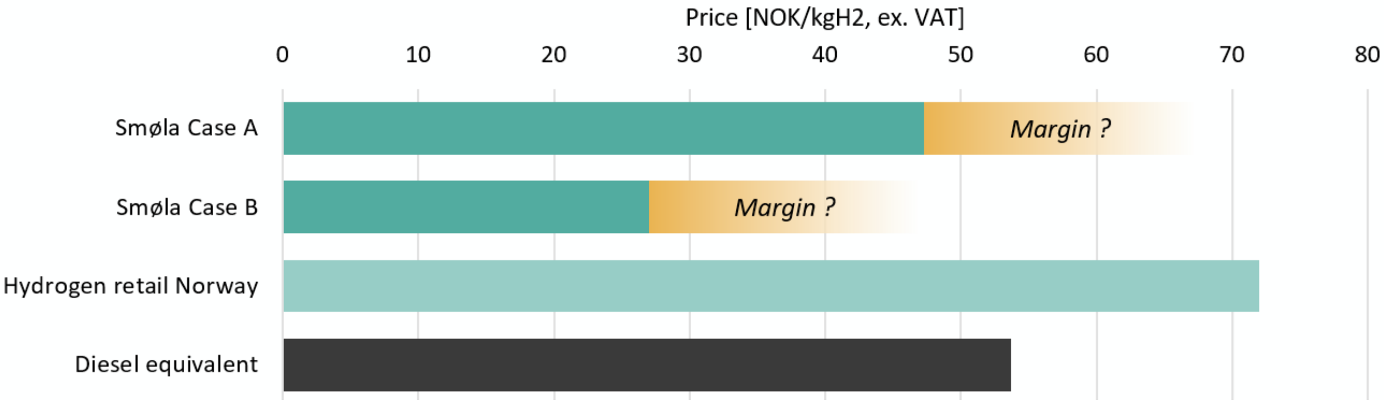

Figure 11 - Hydrogen production cost at Smøla, retail hydrogen price in Norway and diesel equivalent price (pump price for private vehicles, ex. VAT)

In practice, the retail price for hydrogen from Smøla would be higher than the production costs. This is reflected on the figure above with a placeholder for a margin. This margin would most likely vary depending on the type of customers, their willingness to pay, and the volumes procured.

Nevertheless, the figure shows that the hydrogen production costs at Smøla allow for a significant margin while still being competitive with current hydrogen retail prices, and with diesel equivalents (in particular for Case B).

The company in charge of hydrogen sales would be the one setting the hydrogen price for the different markets. The ownership structure for production and sale of hydrogen from Smøla is not defined at this stage and is not within the scope of this assessment. NVES (2018) recommends establishing a development company, co-owned by public and private actors.

Production costs with both case A and case B are close to other Norwegian projects, when taking into account the production capacity. This is illustrated in Figure 12, with a benchmark based on five other projects.

The following projects are the basis for the benchmark:

- Hellesylt Hydrogen Hub (Stranda kommune, 2017),
- Rotnes Bruk (NVE / SINTEF, 2017),
- Kvinnherad (Greensight, 2018a),
- Rullestad (SINTEF, 2018),
- Gloppen (Greensight, 2018b).

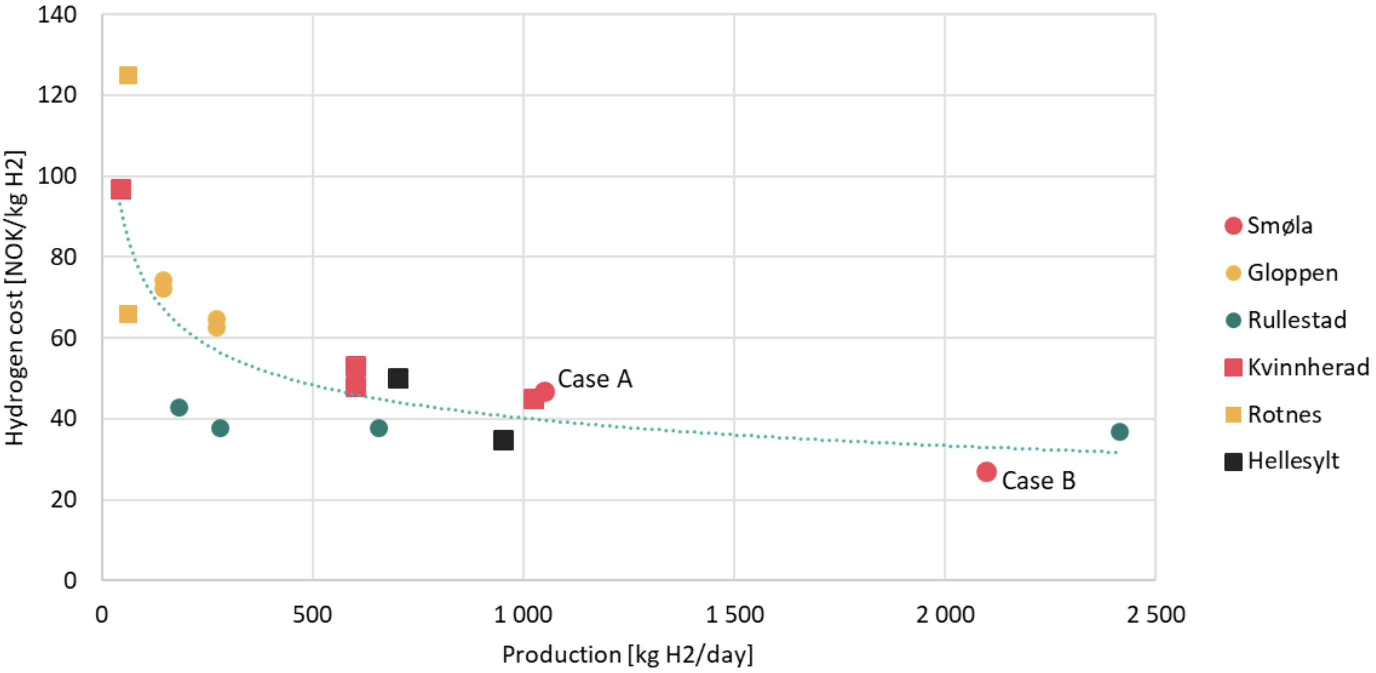

Figure 12 - Correlation between hydrogen production and hydrogen cost for six different projects, including Smøla Case A and Case B

It should be noted that the projects in the figure above have differing assumptions in terms of electricity costs, public support, sale of heat and oxygen, etc., which can explain the variations around the trend line.

The Smøla cases provide competitive production costs even in case of reduced demand: the capacity factor has a moderate impact on the production costs (down to ca. 60% capacity). Refer to appendix C for more details on the sensitivities.

2.2 CASE A - SIMPLE PRODUCTION AT EDØY

Case A is a relatively simple production setup, with production located at an available lot north west of the high speed ferry quay at Edøy. Low pressure hydrogen is sent to compressors located closer to the quay, through a 600 m long pipeline. There, the hydrogen is compressed to 350 bars, and stored in tanks. High pressure hydrogen is then sent to the dispensers at the quay, to fuel the high speed ferries and buses.

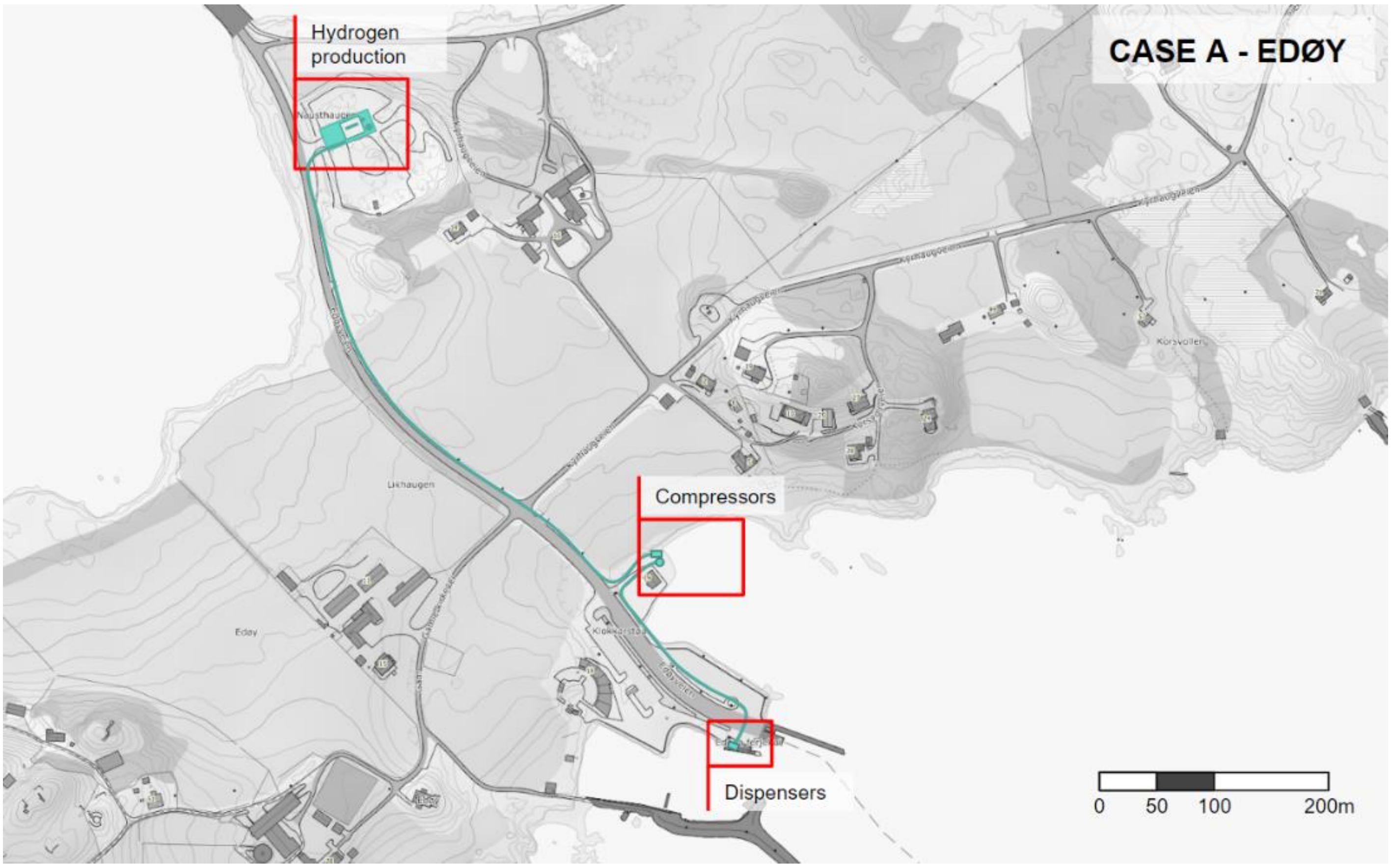

Figure 13 - Map with the location of the main equipment for case A at Edøy (dimensions are approximate)

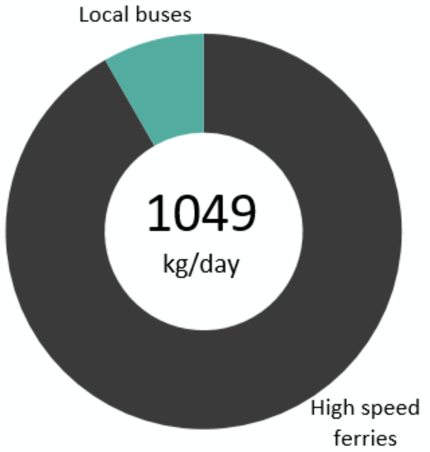

Figure 14 - Hydrogen users with Case A

Case A has a total production capacity of 1,049 kg_{H2}/day, and equivalent of two days' demand in the storage tanks. This allows for ensuring enough supply to the high speed ferries in case of production issues.

Heat and oxygen by-products are not used with case A, due to the lack of users in the immediate vicinity. Similarly, the hydrogen production is only for the high speed ferries and busses, and case A does not have export facilities.

On the longer term, much of the equipment could be used to fill hydrogen cars. This would however require a different type of dispenser, and higher-pressure compressors (700 bar). This is not included in case A at the moment.

Case A

47.3

NOK/kg_{H2}

The break-even price for hydrogen produced with case A is 47.3 NOK/kg. Energy costs make 59 % of the production costs (discounted over the project period), and equipment is the second largest cost contributor (27 %).

The production costs could be reduced to 41.2 NOK/kg_{H2} in case of Pilot-E support to case A.

2.3 CASE B - ADVANCED PRODUCTION AT VIKAN

Case B is relatively more complex than case A, with production located at a future industry area at Vikan (site 2). Hydrogen is compressed to 350 bar on site, and stored in containers on wheels (trailer). These are then transported by truck to Edøy, where they provide hydrogen to the boat and bus dispensers at the quay. One quarter of the total production is to be exported to the region, e.g. to Åndalsnes for use in a hydrogen train. Another quarter of the hydrogen is also to be used locally, either at a dispenser to be installed for local users, or for an industrial site. Heat and oxygen by-products are assumed to be used by a local industry at Vikan, e.g. a fish hatchery.

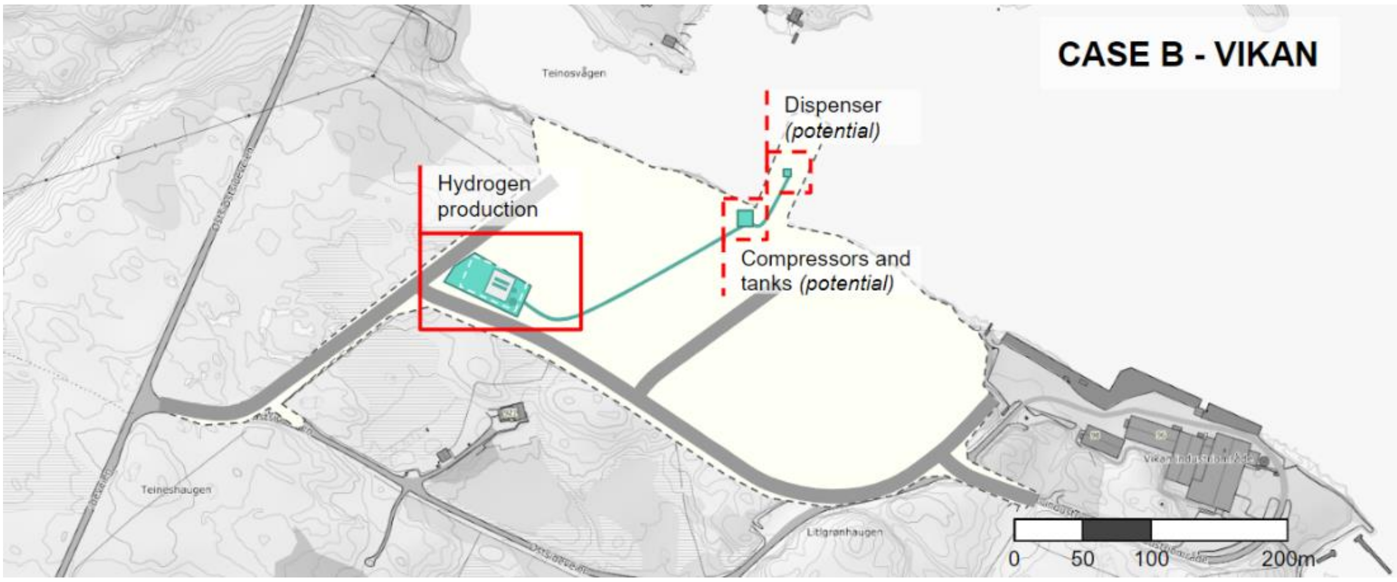

Figure 15 - Map with the location of the main equipment for case B at Vikan (dimensions are approximate)

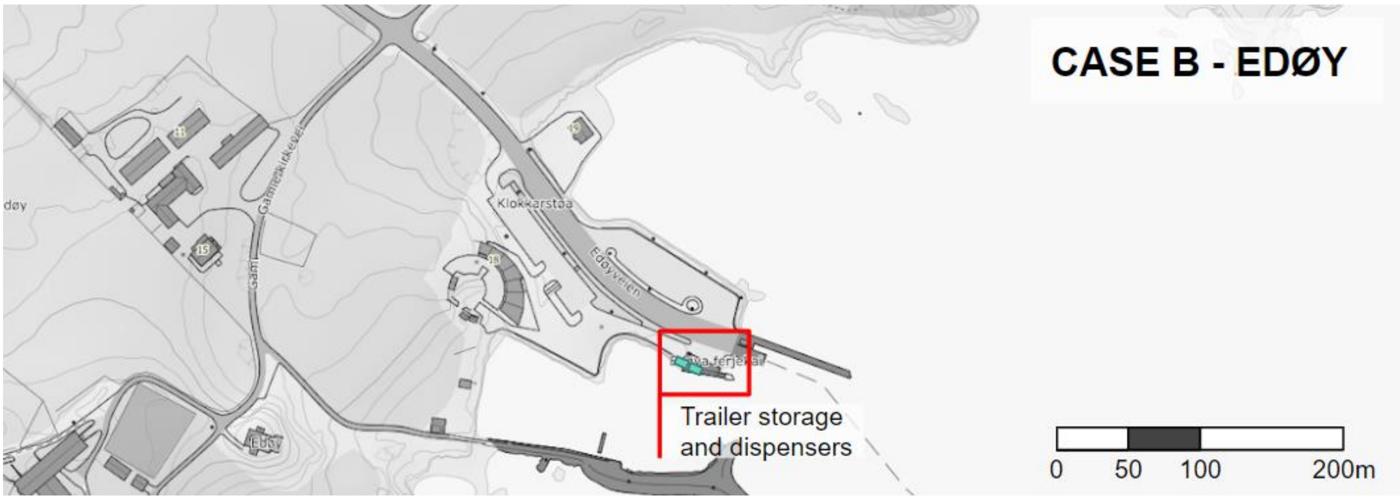

Figure 16 - Map with the location of the distribution equipment for case B at Edøy (dimensions are approximate)

Case B has a total production capacity of 2,098 kg_{H2}/day, and equivalent of roughly two days' demand in fixed storage tanks as well as mobile storage units. This allows for ensuring enough supply to the high speed ferries in case of production issues.

The dispenser at the quay at Vikan is not included in the assessment, and is a potential future extension if there is sufficient local demand. On the short term, it is expected that hydrogen consumers would sail to Edøy for bunkering there.

Similarly to case A, on the longer term, much of the equipment could be used to also fill hydrogen cars. This would also require a different type of dispenser, and higher-pressure compressors (700 bar), which are not included in case B at the moment.

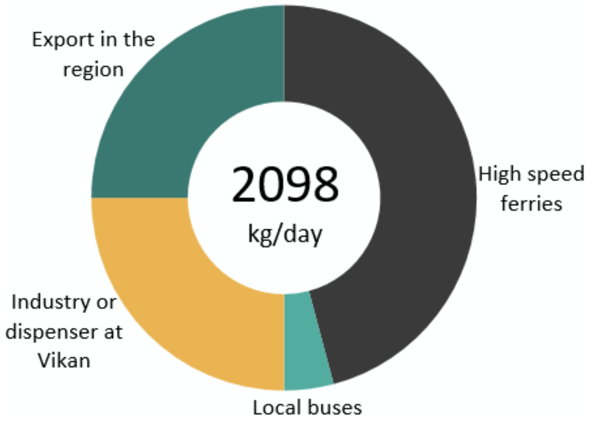

Figure 17 - Hydrogen users with Case B

Case B

27.0

NOK/kg_{H2}

The break-even price for hydrogen produced with case B is 27.0 NOK/kg. This is much lower than in Case A, due to economies of scale, and due to the sale of heat and oxygen by-products. Energy costs make 61 % of the production costs (discounted over the project period), and equipment is the second largest cost contributor (25 %).

The production costs could be reduced to 21.6 NOK/kg_{H2} in case of Pilot-E support to case B.

3 ENVIRONMENTAL AND SAFETY PERSPECTIVE

Safe operations, and environmental benefits compared to fossil fuels are two prerequisites for the feasibility of hydrogen projects in the transport sector. From the environmental perspective, hydrogen from Smøla provides clear benefits in terms of GHG savings compared to diesel. Additional benefits (NOx, particulates, etc.) are more uncertain on a life cycle perspective, but are also clear from an operational perspective (tank to wheel). From a safety perspective, the main concerns are related to the potential impact of special design requirements and new approval processes on the project schedule and cost.

3.1 ENVIRONMENT

Hydrogen has zero direct emissions when used in a fuel cell (tank to wheel). The production of the fuel however leads to GHG emissions, when taking into account the energy needed and the production and maintenance of the equipment (well to tank). A review of research studies relevant for Smøla shows that the indirect GHG footprint of hydrogen production at Smøla would be ca. 1.03 kg_{CO2e}/kg_{H2}, with some uncertainties linked to differences across studies (see appendix D).

The footprint is considered similar for cases A and B, with the exception that case B would include an additional footprint linked to transport of the hydrogen by truck. These emissions are however limited, in particular for shorter transport distances.

Endrava calculated that each kilogram of hydrogen used in replacement of diesel would allow reducing GHG emissions by 13.6 kg_{CO2e}. Conversely, this means that replacing one litre of diesel with hydrogen allows saving 3.05 kg_{CO2e}, as illustrated below. Note that this is a generic value, and there may be variations depending on the type of vehicle.

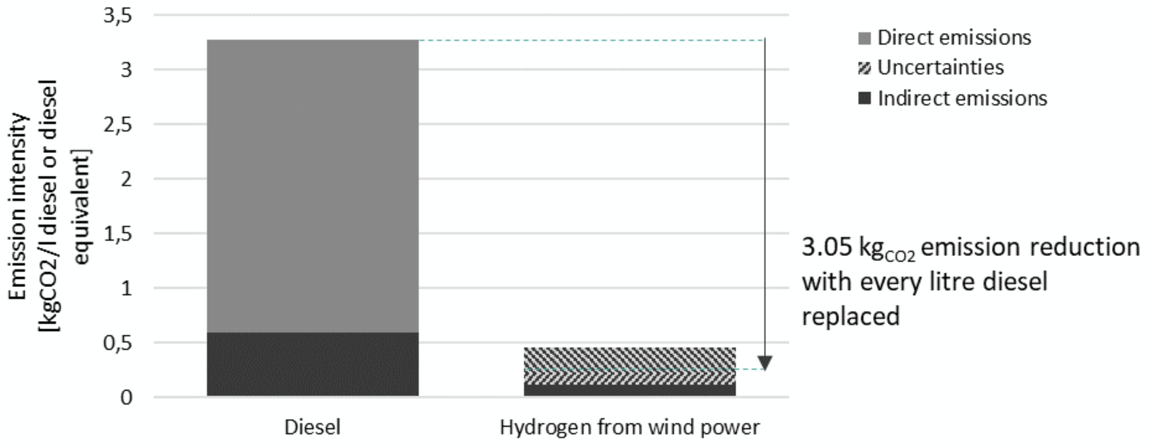

Figure 18 - GHG emission savings with the use of hydrogen instead of diesel in vehicles

Based on the hydrogen production in Case A and Case B (appendix C), with a production capacity of 1.05 $tonnes_{H2}$/day and 2.1 $tonnes_{H2}$/day, respectively, the emission reductions from production of hydrogen at Smøla would be 5,171 $tonnes_{CO2e}$/year for Case A, and 10,342 $tonnes_{CO2e}$/year for Case B. This is based on the assumption that all the hydrogen produced at Smøla would replace the use of diesel.

The use of hydrogen has other environmental benefits, although GHG emissions is usually the main focus. An LCA carried out in 2011 (Simon and Bauer) showed that hydrogen from wind energy has lower NMVOC and NOx emissions than diesel over the entire life cycle (well to wheel). The benefits are less clear for SO_X emissions, and hydrogen from wind could lead to more emissions of particulate matter than diesel. This assessment was however based on a EURO 3 engine, and the results would be different with the newer EURO 6 standards.

3.2 SAFETY

From a safety perspective, the use of hydrogen as a fuel in transport brings new challenges, and most of these are related to the current lack of experience and standards. Existing regulatory and approval frameworks need to be adjusted, and in some cases ad-hoc safety studies need to be undertaken. The complexity of approval and permitting processes is expected to decrease once more projects are carried-out and experience is learnt.

3.2.1 SAFETY IN MARITIME APPLICATIONS

On the overall, the use of hydrogen in maritime applications is not a challenge for the safety of people and assets as long as appropriate design and operational safety measures are implemented. The challenge is related to the fact that this is a new type of fuel, and currently very few guidelines, standards and qualifications are in place. In practice, this means that new, hydrogen-fueled ship projects have to go through a series of custom-made assessments and lengthy approval processes. The outcome of these is uncertain in terms of design and operational implications, and on the time and cost impact to projects.

The text below provide an overview of the status and challenges along a project life-cycle. For further details, refer to HyLAW (2019), DNV GL (2017), SINTEF (2017) and HR Prosjekt (2017).

Within design/type approval, the main challenge is a regulatory gap related to the fact that the use of fuel cells onboard ships is currently not regulated. In practice this means that approval must be sought through a process called Alternative Design approach. This approach is costly and time-consuming, and it was estimated that the whole process can add at least one year to the regular approval process for conventional ships. In addition, HyLAW (2019) mentions the need for technology qualification and development of standards, in particular with regard to possible failure modes, material tests for low temperatures, location of pressurized tanks, and the qualification of the tanks for maritime use.

Ship registration is not expected to be a barrier for the implementation of hydrogen in the maritime sector. Once ships are approved (previous step), only additional documentation requirements may come in, which should not be a challenge.

In terms of operations and maintenance, little is known at the moment about the implications of the use of hydrogen on the operation and maintenance requirements for the ships. As per now, there are no special requirements for hydrogen-powered ships, but the alternative design approach might lead to specific needs. The time and cost implications on the operations are unknown at the moment.

According to HyLAW (2019), there is a knowledge gap and a need for more specific guidelines for onshore landing and bunkering installations. All bunkering of hydrogen for passenger ships require special consent form the Norwegian Directorate for Civil Protection. Applying for special consent is a time-consuming process, and a comprehensive, quantitative risk assessment is required for approval. Risk studies and technology qualification are needed to compensate for the little experience available about the risks related to the use of compressed hydrogen at the moment. This comes at a cost and adds further uncertainty to technological innovation projects.

3.2.2 SAFETY IN ROAD TRANSPORT APPLICATIONS

For road transport applications, safety-related approval procedures and framework are more mature than for maritime applications. This is partly due to the fact that there is per today more experience with the use of hydrogen as a fuel in road transport than in the maritime sector. Part of the approval and permitting process is however handled at the municipal-level, and large differences exist between local authorities.

This creates uncertainties for projects in terms of permitting duration and outcome. In the case of Smøla, support from the local authorities will most likely be key in enabling a faster permitting process and reducing the project risks.

The text below provide an overview of the status and challenges along a project life-cycle. For further details, refer to HyLAW (2019).

In terms of type approval for vehicles, the Norwegian Vehicle Regulation implements the EU Regulation (EC) No 79/2009 on type-approval of hydrogen-powered motor vehicles. According to HyLAW (2019), EU type-approval is generally applicable for hydrogen fuel cell vehicles. However, no general type-approval has been made for hydrogen fuel cell trucks up to now. These will have to go through individual approval, which takes extra time and involves a level of uncertainty for early adopters.

HyLAW (2019) did not identify any restrictions on the use of public road infrastructure for hydrogen powered vehicles.

For the implementation of refueling stations, there are no rules limiting the installation of stations with or without on-site production or storage in certain zones of types of areas. In practice, however, the application for installing a station in commercial or residential areas is reviewed more strictly. If the suggested location does not suit the land use plan, a longer procedure must be undertaken to grant an exemption or change the plan. Experience shows that local factors play an important role in how the implementation of refueling stations happen. The competence and capacity of the municipal authorities varies considerably. In addition, some municipalities have established “fast-track” procedures for the permitting of hydrogen stations, while others take years to process the applications. The permitting process is a three-stage procedure involving a general permit, a construction permit, and an operation permit. The need for notification or consent depends on the amount of hydrogen to be stored (i.e. more than 0.4 m^3, more than 5 tons). Standards for design of refueling stations exist.

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Other references are listed at the end of each appendix.

APPENDIX A - USERS DESCRIPTION

A1. EXTENDED INFORMATION ON OTHER TRANSPORTS

A description of the technological maturity for ferries and buses is provided in section 1.1. The status of hydrogen as a fuel for light duty vehicles, heavy duty vehicles and trains is presented more in detail below.

A1.1 LIGHT DUTY VEHICLES

Fuel Cell Electric Vehicles (FCEVs) are electric vehicles using hydrogen stored in a pressurized tank and a fuel cell for on-board power generation. FCEVs are fueled in 3-4 minutes, the exhaust being only water vapor. Fuel Cell technology has developed significantly in recent years. Today's modern PEM fuel cells have higher efficiency, longer life and lower material costs than they had only a few years ago. FCEVs have reached very high levels of technological maturity and have acquired substantial operational experience in Europe and other key international markets.

FCEVs
- Consumption: 0.95 kg/100 km
- 2 models available in Norway
- Price: ca. 600.000 NOK
- Same advantages as BEVs in Norway
- Range: Ca. 650 km

The market for fuel cell light duty vehicles is limited at the moment, with only two models available in Norway: only Toyota and Hyundai offer FCEVs in the country. One of the biggest obstacles for an accelerated European market uptake is the current lack of availability of commercial products from OEMs (Roland Berger, 2018). In terms of adoption, there where 28 new registrations of FCEVs in Norway from January - May 2019, making a total of 176 registrations per May 2019 (NHF / OFV, 2019).

One of the biggest obstacles for an accelerated European market uptake is the current lack of availability of commercial products from OEMs (Roland Berger, 2018). In Norway, only Toyota and Hyundai offers FCEVs. There where 28 new registrations of FCEVs in Norway from January - May 2019, making a total of 176 registrations per May 2019 (NHF / OFV, 2019). Hyundai Nexo was launched in September 2018. It has a range of 666 km and costs of ca. 585.000 NOK.

Some of the FCEVs in Norway are used by public entities for municipal services, while others are privately owned. Akershus, Oslo, Bergen and other cities are interested in getting more FCEVs as taxis. There are a few Toyota Mira and Hyundai iX35 operating as taxis today, but so far Hyundai hasn't approved that type of use for the Nexo because of warranty issues. Car sharing is another interesting segment. The car-sharing cooperative “Bilkollektivet” used to have 2 Toyota Mirai in Oslo, but they had to remove the vehicles because of lack of infrastructure. In München BeeZero had 50 iX35 FCEVs in their car sharing pool. However, the service was closed because it was not economically viable (BeeZero, 2018).

Figure 19 - Hyundai Nexo, one of two FCEV models currently available in Norway. Photo: Jan Carsten Gjerløw.

A1.2 HEAVY DUTY VEHICLES

For heavy-duty trucks, hydrogen and fuel cells is a promising solution as it does not have the same limitations as battery-electric trucks currently have, in terms of range and charging/fueling time. However large-scale roll-out is yet to begin and so far only initial prototypes have been developed. Many interesting things are happening within this segment. Scania will deliver the first 4 hydrogen trucks to the Norwegian food wholesaler ASKO early 2019 (ASKO, 2019). However, there are no indications from Scania that they will continue development and manufacturing of FC trucks.

Hyundai FC Truck

- Range: 400 km
- 35 kg$_{H2}$ on board, 350 bar
- Consumption: 8.8 kg/100 km
- 1000 trucks delivered to Switzerland by 2023
- First trucks to Norway possible in 2020

In Switzerland, H2 Energy and Hyundai Trucks have a very interesting initiative: 1000 FC trucks will be delivered from 2019 to 2023, starting with ca. 10 trucks in 2019 and several hundred in 2023 (H2 Energy, 2018). The trucks will be available to Swiss customers starting with the dedicated members of the Swiss H2 Association, including refueling-station operators, retailers and others. Hyundai has mentioned Norway as a natural second country for roll-out in Europe, the first trucks may be delivered in 2020 (Freymueller, 2019). Nikola presented their model Nikola Tre dedicated to the European market in April 2019. Testing is scheduled to start in Norway together with Nel in 2020, and mass production from 2022-2023 (Nikola, 2018). The range will be from 500 – 1200 km, depending on the model.

There is a large interest in Nikola Tre. Several Norwegian companies have made reservations, for instance the Norwegian agricultural cooperative Felleskjøpet reserved 50 trucks (Gasworld, 2019). We see several regional initiatives for fostering deployment of hydrogen trucks in Norway. Akershus county and Hordaland county have ongoing projects or will support projects, and several other counties, cities and municipalities have shown a strong interest for getting zero emission trucks on the road. Delivery vans and waste collection trucks are other interesting applications. Still no vehicles are commercially available, but several demonstration projects are being carried out.

Figure 20 - 1000 Hyundai Trucks will be delivered to the Swiss market until 2023. Illustration: Hyundai

A1.3 HYDROGEN TRAINS

Hydrogen trains seem to be the only viable zero-emission alternative for regional train services operating on non-electrified lines. The world's two first hydrogen passenger trains have been part of the commercial service in Lower Saxony, Germany, since September 2018. The Coradia iLint is developed by Alstom, one of Europe’s largest railway manufacturers.

Hydrogen trains

- Consumption: 25 kg/100 km
- First two in operation since Sept. 2018
- Operates a 100 km line
- Range: 1.000 km
- Max speed: 140km/h

Even though the first FC train demonstration is only just starting, ambitious plans exist to scale up FC train deployments in the coming years. LVNG, the organization responsible for public transportation in Lower Saxony, has already ordered a further 14 hydrogen trains from Alstom, which are scheduled to start driving this route within the next two years, and is considering replacing its entire 126-train fleet with hydrogen-powered locomotives (Expat, 2019). According to Alstom, several other countries are also looking into hydrogen trains, including Britain, the Netherlands, Denmark, Norway, Italy and Canada. French National Railways (SNCF) announced late 2018 that it has committed to bringing the first hydrogen fuel-cell train in France into operation by 2022 (IRJ, 2018). In January 2019, Alstom and Eversholt Rail Group unveiled the design for a new hydrogen fuel cell train, nicknamed ‘Breeze’, for the UK market. Alstom expects orders for the train by the end of 2019 (Railway Gazette, 2019). The potential use of hydrogen and fuel cells is also being explored in other rail segments, these are however for the moment demonstration projects only.

Three major rail lines in Norway that are not electrified - Nordlandsbanen, Rørosbanen and Raumabanen. The Norwegian government’s agency for railway services, Bane NOR (former Jernbaneverket), has conducted a study on the railway lines in Norway that are to be electrified (Jernbanedirektoratet, 2015). SINTEF has assisted Jernbaneverket with a comprehensive report on options for the electrification of the rail network (SINTEF, 2015). The report concludes that hybrid hydrogen and battery operation is a highly recommended solution for many of today lines operated by diesel-electric trains. Raumabanen is particularly interesting, since for various reasons it is irrelevant for electrification using contact wires. NVES (2018) described several positive effects of using hydrogen for the Rauma line. The Coradia iLint used in Lower Saxony may be used on the Rauma line with minor modifications, and will increase the number of seats by approximately 50%. This is well in line with targets for passenger traffic growth. Use of hydrogen on the Rauma Line will together with hydrogen infrastructure at Åndalsnes give great opportunities for ripple effects such as the decarbonization of transport of goods by road and sustainable growth in tourism. The use of hydrogen for the zero-emission operation of trains, tourist buses, boats and more will contribute to the growth of the tourist industry being combined with sustainability.

Figure 21 - Coradia iLint is now in commercial service in Lower Saxony. Photo: René Frampe_evb_coradia iLint

A1.4 OTHER MARITIME USERS

High speed ferries and passenger vessels are not the only maritime segments where hydrogen applications are being developed. Several projects are underway for applying fuel cell technologies to fishing vessels in Norway, France and Japan for example (TU 2017, Mer et Marine 2018, Safety4Sea 2019). If successful, the implementation of hydrogen as a fuel to the fishing sector could lead to a large hydrogen demand in Møre and Romsdal, since it is estimated that ca. 80% of the Norwegian sea fishing fleet bunkers in Ålesund (Energigass Norge, 2015).

Figure 22 - Karoline, the world's first electric vessel, which may be converted to hydrogen. Photo: Siemens

Hydrogen technology is also relevant for other types of vessels within the fish industry. Kyst.no (2018) describes a design for a fish farm service vessel. NVE (2017) also mentions the potential to convert a live fish carrier (*brønnbåt*) to hydrogen, and estimates the consumption to 273 tonnes$_{H2}$/year. The study does not however assess the feasibility of such a conversion, nor does it refer to specific project for the boat.

The multimodal operator Samskip is now leading a project to develop two hydrogen-fueled container ships for short-sea routes between Oslo, Poland and the western coast of Sweden (Samskip, 2018). The project received a Pilot-E grant from the Norwegian government.

Much of these maritime projects are at the concept or pilot stage, and the potential for future implementation of the technologies is still unknown. DNV GL (2018) analyzed the use of hydrogen as a measure for reduction of GHG emissions in the maritime sector, with 2030 as time horizon. The study mentions that hydrogen is best suited to newbuilds due to technical constraints, as opposed to ship conversions. The techno-economic analysis carried-out by DNV GL shows that the technology is most suitable for passenger ships with gross tonnage below 9,999.

Hydrogen could also be used as a fuel to produce electricity and oxygen for coastal fish farms, as mentioned by iLaks.no (2018). More and more of the Norwegian fish farms are being electrified from shore, but fuel cell technologies could be cost-effective for farms located in remote areas.

A2. EXTENDED INFORMATION ON COST ELEMENTS FOR HYDROGEN BUSES

European projects such as JIVE 1 and JIVE 2 are currently deploying several hundred hydrogen buses in cities and regions in Europe (FuelCellBuses.eu, 2019). A new EU project called H2Bus Europe, starting in 2019 with Nel Hydrogen as consortium leader, will deploy a total of 600 hydrogen buses in the UK, Denmark and Latvia as a first phase (H2Bus, 2019). Ruter, the public transport company in Oslo and Akershus, has been operating 5 hydrogen buses since 2012 as part of the CHIC project (Ruter, 2017). Ruter is now participating in JIVE 2 aiming to have 10 more hydrogen buses on the road (FuelCellBuses.eu, 2019). Ruter has achieved funding from JIVE (14 MNOK) and Enova (38 MNOK) for the project.

Experience shows that while urban buses (class 1) can be delivered by several manufacturers, regional buses (class 2) are still difficult to acquire. Ruter was aiming for using hydrogen class 2 buses for their services in Akershus west. Two OEMs offered class 2 buses, but the infrastructure was more expensive than estimated. At the time of writing it is uncertain whether the project will be implemented. Ruter seems to rely on Battery Electric buses for the urban routes, while hydrogen buses are considered necessary for the regional routes to be emission free. For public transport in Norway to become zero emission, the availability of class 2 hydrogen buses is thus important, and it is expected that the Ruter project can help making the buses available.

Buying and using FC buses currently comes with an additional cost, which are described in the sections below.

A2.1 COST OF BUSES

There is for the moment a considerable additional cost for FC Buses compared to conventional diesel models. The JIVE 2 project has as an ambition to achieve a maximum price of €625,000 for a standard fuel cell bus of Class 1 (city bus). For Class 2 buses (regional buses) there are no such targets. However, Ruter has set a target of €675,000 for their project. A comparable Class 2 diesel bus costs about €230,000.

The cost for FC buses will be reduced as production volumes increase. Figure 23 below shows an experience curve for class 1 FC buses. The price has come down with every new demonstration project. The H2Bus Europe project, aiming for deploying 600 buses, is expected to bring the price further down. Large-scale Chinese projects have reduced the price to almost diesel parity, as illustrated below.

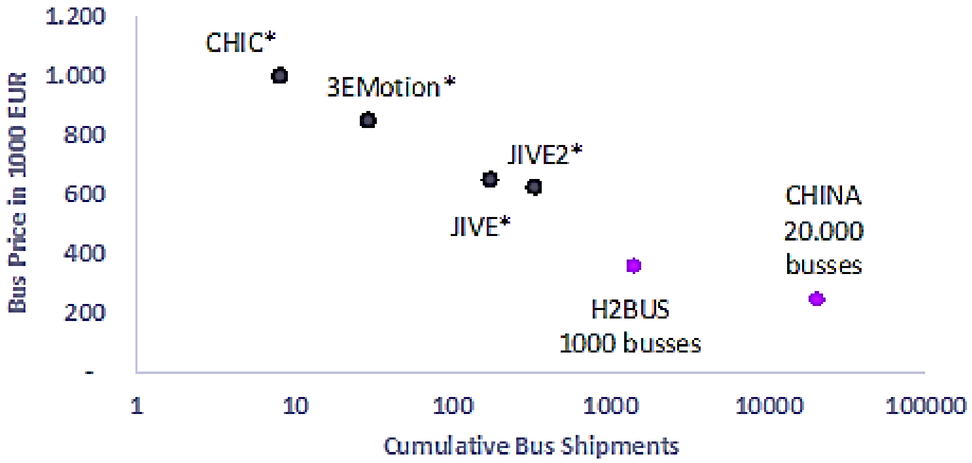

Figure 23 - Experience curve for FC buses of class 1. Source: Nel, 2017

Economy of scale: A minimum amount of buses is required to get attention from bus manufacturers. Especially if adjustments to standard specifications of the bus are needed. The cost per bus will depend on the size of the order.

A2.2 BUS INFRASTRUCTURE COSTS

In terms of infrastructure, different strategies can be used: refueling can be done at hydrogen fuel stations located in the area or at the bus depot. Bus operators usually prefer fueling at the depot, to minimize the distance and time spent refueling.

If hydrogen is made available at the depot, this can either be from a dedicated station there, or from a public station next to the depot serving both buses and other vehicles. The latter will help making the operation of the station more economically viable, and will help the deployment of hydrogen passenger vehicles and trucks.

It is also possible to share a station between the depot and the public on the other side of the fence. This type of station will require some additional infrastructure cost at the depot. The cost will be dependent on the size of the fleet.

Different ways of refueling may be selected as well: slow or normal speed, and the first is most likely cheaper. Buses may also be refueled at a public station using the same dispenser as for trucks. This may however be a challenge when it comes to refueling queues - waiting times should be avoided because of the typically tight time schedules for buses. Redundancy of the fueling systems is important to ensure high reliability.

Economy of scale: Some of the investments will be depending on the size of the fleet, some initial costs are regardless of the size.

A2.3 BUS FUEL COSTS

The fuel costs for hydrogen buses depend on how the fuel is made available. Long distance transport of the fuel gives a high transport cost but the production price may be low if it is made at large scale. On-site production may be expensive if the volume is low.

Ruter reported fuel costs of 11-15 €/kg for the 5 buses in the CHIC-project (i.e. 108 to 147 NOK/kg). The EU project New Bus Fuel (NewBusFuel, 2017) estimated a cost of ca. 7 €/kg (69 NOK/kg) with a production volume of 1,000 kg/day. A conservative estimate will be 8 €/kg (78 NOK/kg) for the hydrogen, which is slightly more than the current cost of 72 NOK/kg (ex. VAT) at the refueling stations in Norway.

For the fuel consumption we may assume 0.1 kg_{H2}/km, and 0.45$litre_{diesel}$/km for diesel buses. The diesel price for buses is about 1€/l. The cost per km is then 0.8€ for hydrogen and 0.45 € for diesel, thus 1.7 times higher with hydrogen.

Economy of scale: A small number of buses may give a high fuel cost. The JIVE project suggests a minimum of 10 buses in a fleet. Experiences from Ruter show that the number even should be higher in order to achieve good solutions for the infrastructure and acceptable fuel costs.

A2.4 BUS MAINTENANCE COSTS

Maintenance cost is higher for hydrogen buses than diesel buses in the initial phase. This is because of more expensive spare parts, the need for special competence and the need for safety precautions at the workshop. There will be an initial cost and an operational cost per bus.

Roland Berger (2018) estimated the additional maintenance cost for a Class 1 FC bus to be ca. 40% higher than for an equivalent diesel bus. For a class 2 bus it may be higher, since the total number of deployed FC buses is almost zero, and the value chain is less mature. Thus, an increase in maintenance cost between 50% and 100% compared to an equivalent diesel bus may be expected.

Economy of scale: There is a dependence on the size of the fleet, but also a quite high initial cost. The cost per bus will be lower with a higher number of buses. The cost will also go down as the total number of buses deployed increases, making the supply chain more mature.

A2.5 OTHER COSTS

FC buses are procured by few bus operators so far and there is a larger need for expert assistance in the procurement process. Competence building is needed in organizations as well, and personnel at different levels in the organization need to be trained. Increased costs for project management and marketing should be expected too.

Economy of scale: These costs are independent of the size of the fleet. The cost per bus decreases with a larger fleet.

A2.6 TOTAL COST OF OWNERSHIP FOR HYDROGEN BUSES

FC buses are currently more expensive than diesel equivalents on most of the cost categories, and the size of the fleet matters. It is in general not recommended to acquire a too small fleet since it will not give the necessary attention from the suppliers, and it will bring the procurement and operations cost per bus to a high level.

Roland Berger (2017) estimates that the TCO of hydrogen buses is currently 30 to 40% higher than for diesel buses, as shown in Figure 24 below. The potential in the long term is a TCO that is 5 to 10% higher. This is based on a large-scale production of FC buses.

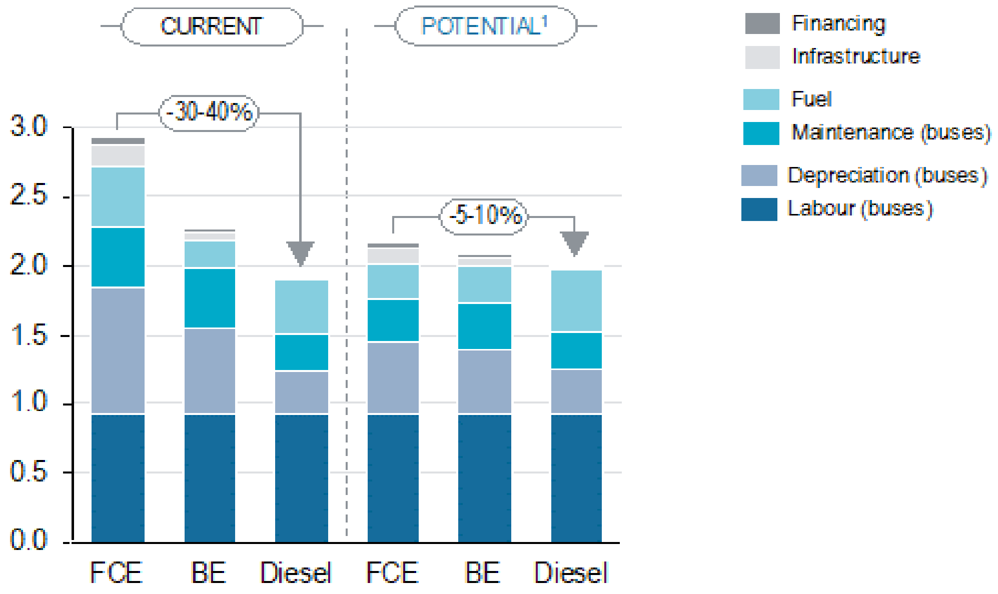

Figure 24 - TCO annualized at 2017 prices for fuel cell (FCE), battery-electric (BE) and conventional diesel buses, in €/km. The "potential" scenario requires a number of FC-related and other factors to fall into place in the medium/long run. Source: Roland Berger (2018)

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APPENDIX B - DEMAND ANALYSIS

B1 FERRIES ON THE LINE TRONDHEIM - BREKSTAD - KRISTIANSUND

On the short term, high speed ferries are expected to be the main hydrogen consumer at Smøla; a detailed analysis of the potential hydrogen consumption was therefore carried-out as part of the project and is presented here.

B1.1 BACKGROUND ABOUT THE FERRIES AND THE LINE TRONDHEIM - BREKSTAD - KRISTIANSUND

There are currently two high speed ferries on the line Trondheim - Brekstad - Kristiansund, operated by FosenNamsos: MS Terningen and MS Tyrhaug. The main characteristics of the current ferries are presented in the table below.

Table 1 - Main characteristics of the current high speed ferries (source: Brødrene Aa, 2019)

Name	MS Terningen and MS Tyrhaug
Ship type	Catamaran
Built	2014
MMSI nbr.	257333000 and 257684700, respectively
Dimensions	L: 40.8m, W: 10.8m
Main motors	2x Waterjets 16V2000 M72 MTU diesel, 2884 kW 2x Caterpillar auxiliary motors
Power	600 horsepower
Capacity	275 passengers
Gross Tonnage (GT)	492
Max/service speed	36/34 kn

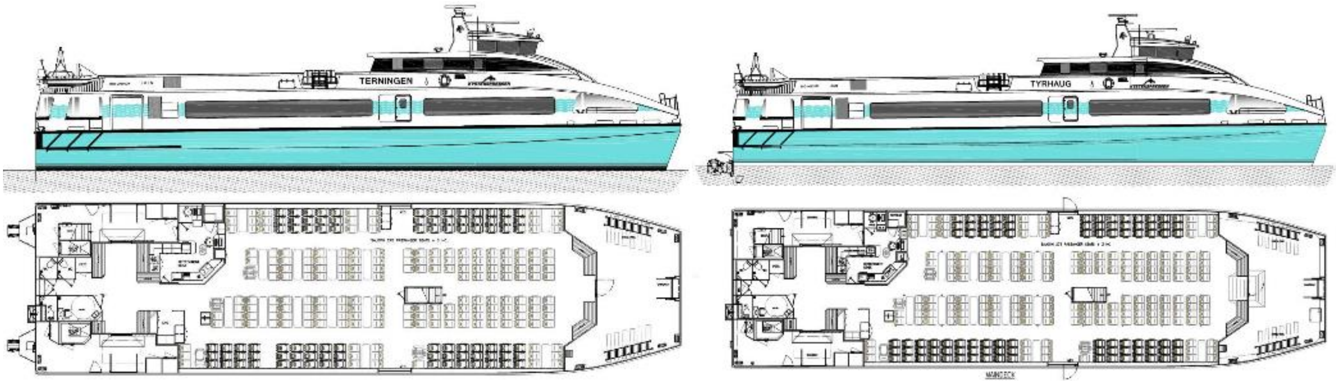

Figure 25 - Illustration of the current high speed ferries. Left: MS Terningen, right: MS Tyrhaug (the boats are almost identical). Source: Brødrene Aa

The line Trondheim - Brekstad - Kristiansund has a total of 9 stops (AtB, 2019), and covers a distance of 92.5 nautical miles (Øgård, 2017). It is illustrated in the figure below. At night, one ferry is located at Edøy, and the other at Brekstad.

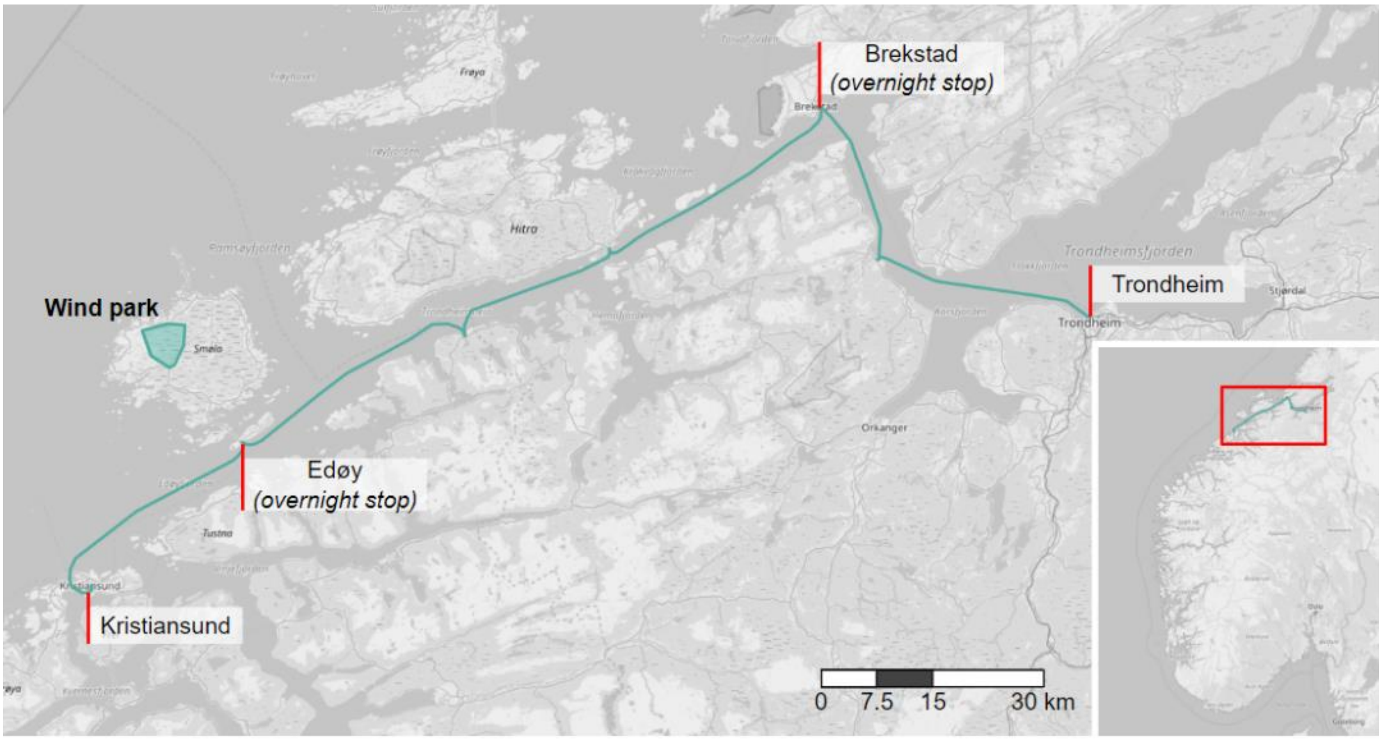

Figure 26 - High speed ferry line Trondheim - Brekstad - Kristiansund. Source: Endrava

B1.2 DEMAND ASSESSMENT FOR THE FERRIES

B1.2a Case 1 - Current route structure, today's energy consumption

SINTEF (2017) reports an energy use of ca. 6,000 kWh per high speed ferry, to cover the whole route from end to end. Assuming an electrical energy output of 17 kWh/kg$_{H2}$, the high speed ferries would consume 353 kg$_{H2}$ per stretch based on today's energy consumption. This is equivalent to 3.82 kg$_{H2}$/nm.

In addition to the fuel required for a whole stretch, the high speed ferry would need to carry a safety buffer. An additional 50 kg$_{H2}$ is therefore required in order to ensure that the ferry would have sufficient fuel in case of high wind or currents, or unexpected change in route. This corresponds to a total required storage capacity of 403 kg_{H2}. A design with three tanks, each with a 150 kg_{H2} capacity, is selected. This is in line with the calculations made by SINTEF (2017).

Based on these characteristics and assumptions, the fuel use and tank levels for each ferry was simulated for a typical day, based on the existing overall schedule as published by AtB (2019), and on the distance between each stop. In case 1, the ferries would fill-up their tanks at Trondheim at one end, and at Edøy at the other end of the route.

Small adjustments were made to the current time-table, to allow enough time filling hydrogen at Edøy. A maximum allowable stop time of 12 minutes at Edøy was included in the calculations, including 5 minutes for bunkering preparation and disconnection. This corresponds to a maximum bunkering time of 7 minutes. A bunkering speed of 22,5 kg_{H2}/min is assumed. Two dispensers would be required to attain this speed. The resulting tank level (black lines) and filling amounts (green columns) are presented in the figures below.

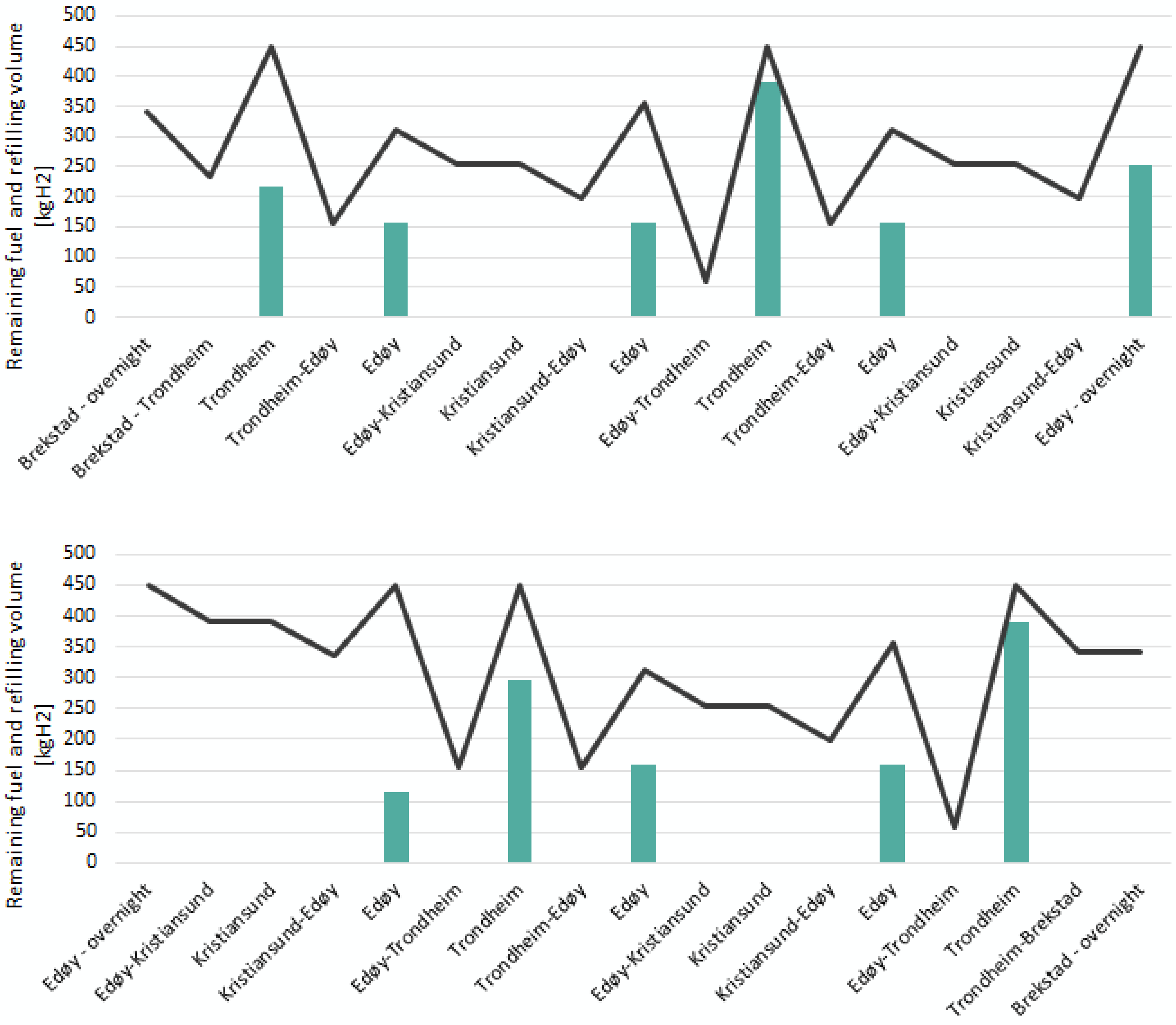

Figure 27 - Case 1 - Tank level and filling amounts for the ferry starting the day at Brekstad (top), and the one starting at Edøy (bottom)

With case 1, a total of 1,155 kg$_{H2}$ would be bunkered at Edøy each day, and 1,294 kg$_{H2}$ at Trondheim. This case demonstrates that with sufficient bunkering at Edøy, no hydrogen filling is needed at Kristiansund. This is based on the assumption that three daily stops of 12 minutes are allowable at Edøy. This could be compensated by a faster travelling speed of ca. 1.5 knot, to keep the overall travelling time from end to end of the route the same as the one today.

B1.2b Case 2 - Current route structure, lower consumption, focus on reducing stops at Edøy

Due to design constraints, it is assumed that the existing high speed ferries will not be converted to hydrogen, and that newbuilds would be needed instead. This would also be an opportunity to optimize the boat design, and it could allow for energy savings compared to the existing ones. The second case is therefore an optimized solution with a lower energy consumption due to an optimized ferry design. In case 2, today's energy consumption is estimated to be reduced by 30%, down to 4,200 kWh per ferry per stretch. This corresponds to a total hydrogen consumption of 247 kg$_{H2}$, or 2.67 kg$_{H2}$/nm, with the assumption of 30% reduced consumption based on ongoing developments in the consortia working in the project "Fremtidens Hurtigbåt" for Trøndelag Fylkeskommune. A total fuel capacity of 297 kg$_{H2}$ would be required onboard the ferry, including 50 kg$_{H2}$ safety buffer. As a conservative assumption, case 2 is based on the same total hydrogen storage capacity as case 1, that is to say three tanks with 150 kg$_{H2}$ capacity each.

Case 2 is optimized in order to reduce the stopping time at Edøy during rush hours, i.e. in the morning and the evening. Therefore, the bunkering volume and time are minimized, and only a 10 minutes' stop is required in the middle of the day, to allow for 5 minutes filling at Edøy. A bunkering speed of 22,5 kg$_{H2}$/min is assumed. The resulting tank level and filling amounts are presented in the figures below.

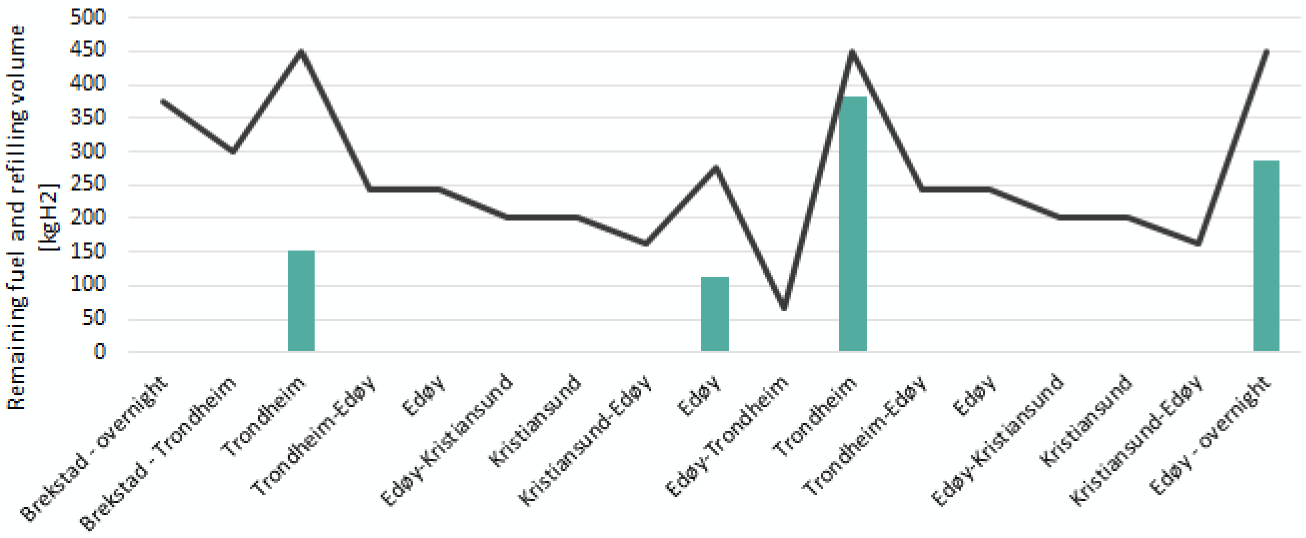

Figure 28 - Case 2 - Tank level and filling amounts for the ferry starting the day at Brekstad

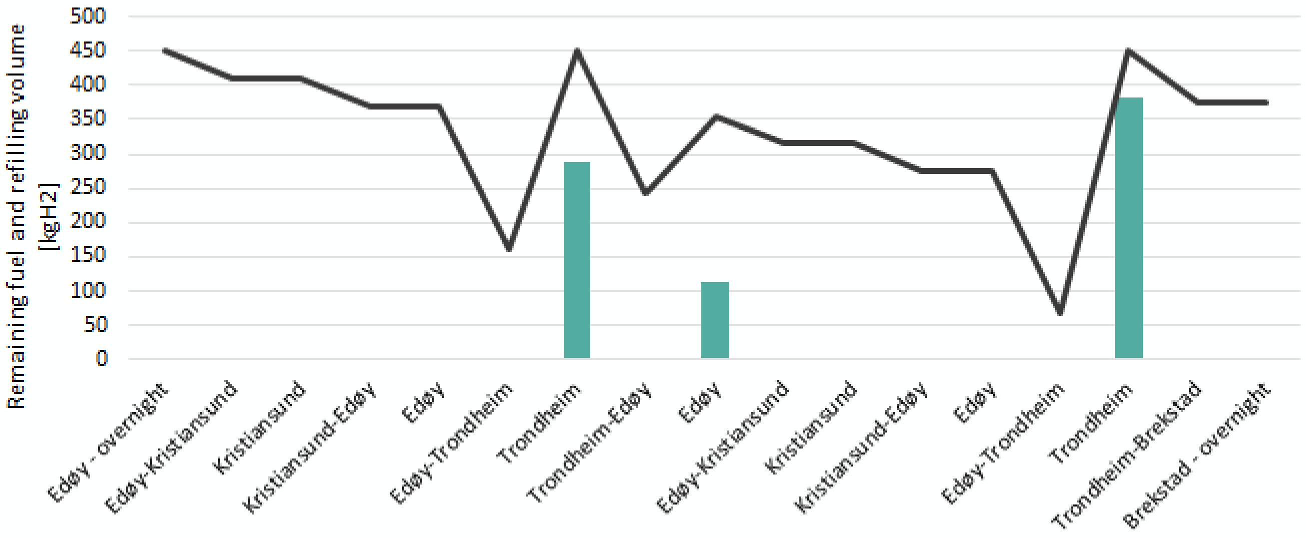

Figure 29 - Case 2 - Tank level and filling amounts for the ferry starting the day at Edøy

With the optimization of the bunkering volumes and time for case 2, a total of only 512 kg_{H2} would be bunkered at Edøy each day, and 1,202 kg_{H2} at Trondheim. This case shows that optimizations can make it possible to reduce the stopping time at Edøy, minimizing disruptions to the current time-table for the ferries.

With sufficient bunkering at Trondheim, only one filling stop is needed at Edøy during the day, and that stop can be limited to 10 minutes. The necessary bunkering time at Trondheim is within the existing stop times on the timetable and would not impact the high speed ferry schedule.

B1.2c Case 3 - Current route structure, lower consumption, supply at Edøy and Kristiansund

The third case is a test to see if bunkering is required at Trondheim. Assuming the same optimized energy consumption (4,200 kWh) and filling speed (22,5 kg_{H2}/min) as in case 2, the calculations show that the ferry would run out of fuel before reaching Edøy on the way back from Trondheim. The distance Edøy-Trondheim and return is too long for the ferry staying at Brekstad overnight to be able to complete its route. At least one hydrogen filling location is therefore needed at each side of the line Trondheim - Brekstad - Kristiansund.

B1.3 TIMEFRAME FOR THE HYDROGEN DEMAND FROM FERRIES AT SMØLA

The high speed ferries sail ca. 320 nm per vessel on weekdays, 135 nm on Saturdays and 228 nm on Sundays. On a weekly basis, the sailing distance is therefore 1965 nm per vessel.

With case 1 (current route structure, today's energy consumption), the hydrogen consumption would reach 15.02 tonnes per week, and 781 tonnes per year. Of this demand, 368 tonnes would be bunkered at Edøy, and the remaining at Trondheim.

With case 2 (current route structure, lower consumption, focus on reducing stops at Edøy), the hydrogen consumption would reach 10.51 tonnes per week, and 547 tonnes per year. A total of 163 tonnes would be bunkered at Edøy, and the remaining at Trondheim.

The existing contract for the high speed ferries ends in January 2022, with an option for two more years (Kollektivtrafikkforeningen, 2018). The option has been called, and it is therefore most likely that the new ferries would come in operation from 2024.

The resulting hydrogen demand is illustrated in the figure below. Note: it presents only the hydrogen demand at Edøy.

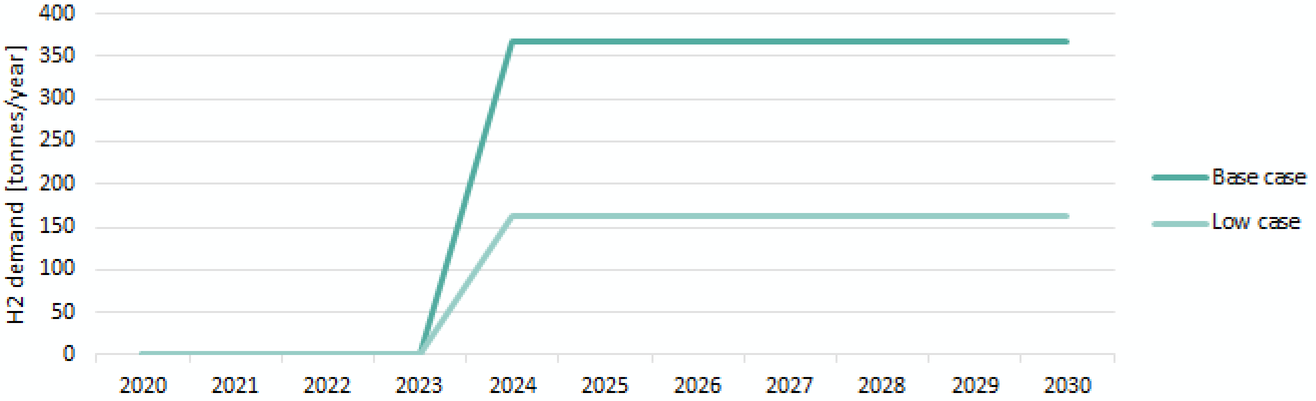

Figure 30 - Potential hydrogen demand from high speed ferries at Smøla / Edøy

B2 AMBULANCE BOAT

The project scope of work included an assessment for the conversion of the ambulance boat MS Øyvakt to hydrogen. Based on data from Brødrene Aa AS (pers. comm. Ole Andre Aa), and on AIS data from the ship (Vessel Tracker, 2018), the project team assessed the potential hydrogen consumption of the boat to be between 121 and 372 kg_{H2}/day, depending on the activity level of the boat. The average consumption calculated over 14 days in October 2018 is 202 kg_{H2}/day.

The boat has a tank capacity of 3,000 liter diesel, which is equivalent to ca. 815 kg_{H2}. In order to ensure an equivalent range than with diesel, five to six hydrogen tanks, with 150 kg capacity each, would need to be installed.

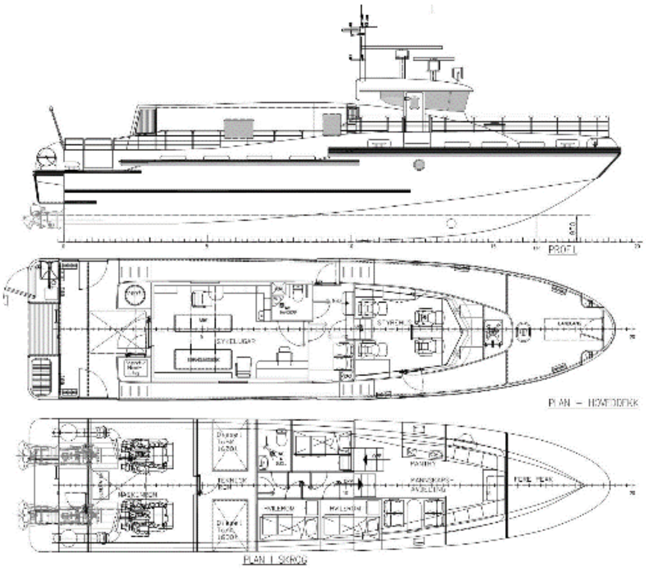

Figure 31 - Technical drawing of the ambulance boat MS Øyvakt (source: Brødrene Aa AS)

This equipment would weigh about 13 tons. It is considered unlikely that this would be compatible with the design parameters for the boat, given the requirements for room, stability and safety. Installing a smaller amount of tanks would lead to a more restricted range, which would not be compatible with the required specifications for the ambulance service.

The ambulance boat is therefore not included further in the list of potential hydrogen consumers at Smøla on a short to medium term. On the longer term, when hydrogen technologies for the maritime sector improve, a new design of the ambulance boat might allow it to use hydrogen as a fuel.

B3 BUSES AT SMØLA

There are two buses on Smøla, and they cover a daily distance of 870 km on school days (NVES, 2017). Assuming that the buses are Class 2 (regional), their hydrogen consumption would be ca. 10 kg_{H2}/100km. This is in the lower range of the hydrogen consumption figures based on experience from projects in Oslo and in Vancouver, as described by NVES (2017).

Based on these assumptions, the buses would consume 87 kg_{H2} on a daily basis (school days), and 435 kg_{H2} on a weekly basis. Assuming 44 weeks of operation during the year, the consumption amounts to 19 $tonnes_{H2}$/year.

The buses are operated by Tide Buss AS, and the current contract expires January 2024, with an option for one more year (Kollektivtrafikkforeningen, 2019). The figure below illustrates the potential hydrogen demand from buses at Smøla. The low case corresponds to the extension of the current contract for one year.

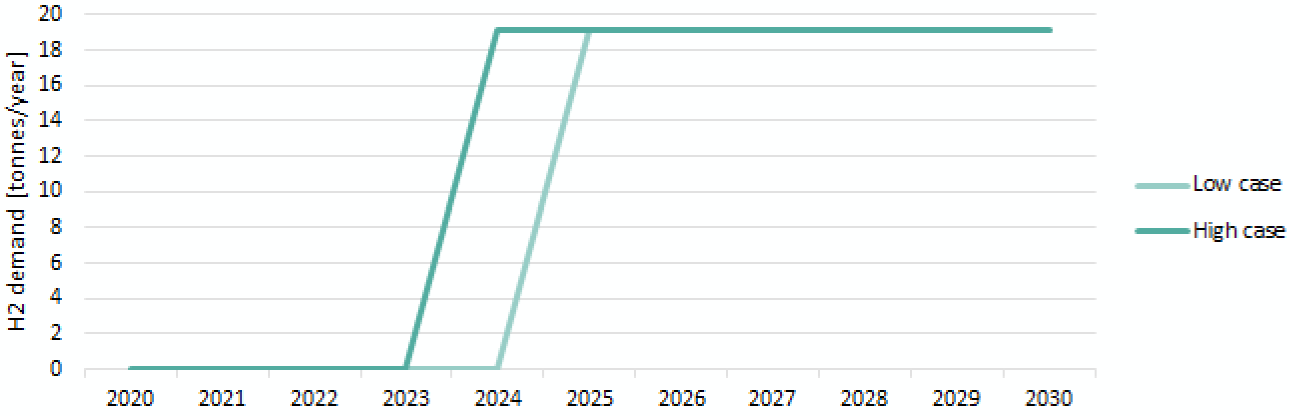

Figure 32 - Potential hydrogen demand from buses at Smøla

B4 CARS AT SMØLA

In the Møre and Romsdal county, cars are driven on average 11,598 km/year (OFV, 2018). Hyundai (2019) indicates a fuel consumption of 0.95 kg_{H2}/100 km. An average car in the county would therefore consume 0.11 $tonnes_{H2}$/year.

There are currently 1,151 cars registered at Smøla (Statistics Norway, 2019), and none of them is using hydrogen fuel. Assuming a gradual phase-in of hydrogen cars at Smøla with 2% of the cars in 2025 and 5% in 2030, and a stable car fleet, the local hydrogen demand from cars could reach 2.5 tonnes/year in 2025 and 6.3 tonnes/year in 2030.

The figure below illustrates the potential hydrogen demand. The high case is the one mentioned above, while the low case is based on 50% of the demand from the high case.

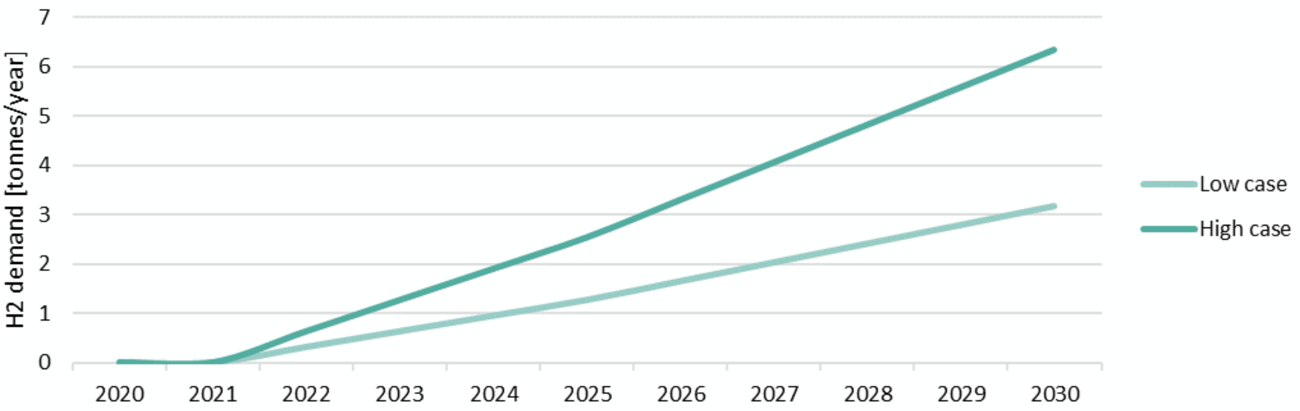

Figure 33 - Potential hydrogen demand from cars at Smøla

B5 HEAVY-DUTY VEHICLES AT SMØLA

According to NVES, very few trucks drive at Smøla, a few transport vegetables and others deliver supplies to the local shops. Fish are transported by other means. Trucks are therefore considered to make a very small contribution to the potential local hydrogen consumption at Smøla and are not assessed further in this report.

B6 OTHER USERS IN THE REGION

B6.1 CARS

The registration statistics indicate 143,579 cars in Møre and Romsdal county (Statistics Norway, 2019). Assuming a gradual phase-in of hydrogen cars in the county, with 1% of all cars in 2025 and 3% in 2030, the total hydrogen demand from cars could reach 158 tonnes$_{H2}$/year in 2025 and 475 tonnes$_{H2}$/year in 2030. This is based on a yearly consumption of 0.11 tonne$_{H2}$ per car, refer to section “cars at Smøla” for details.

The share of hydrogen car assumed for the whole county (1% and 3%) is lower than the share assumed at Smøla (2% and 5%). A larger share of the inhabitants at Smøla could choose to buy a hydrogen vehicle if the fuel is available and produced locally, and this is reflected in these figures.

B6.2 BUSES

For buses in the county, a total of eight route packages from public contracts were analyzed. These eight routes are served by an estimated total of 456 buses, which cover a distance of 17,720,000 km on a yearly basis (Kollektivtrafikkforeningen, 2019).

The current contracts for these routes expire between 2020 and 2027, depending on the route, as presented in the table below.

Table 2 - Main characteristics of the route packages in the county (Kollektivtrafikkforeningen, 2019)

Contract route	New contract start date	Number of buses (estimated)	Yearly distance [km]
Route package 1: Ålesund, Giske, Sula	01/01/2020	80	3,000,000
Route package 2: Kristiansund, Averøy, Smøla & Aure	01/01/2024	50	2,300,000
Route package 3: Molde & Gjemnes	01/01/2025	25	1,038,700
Route package 4: Express Ålesund-Kristiansund, Ålesund-Åndalsnes, some regional and school routes	01/01/2025	80	2,925,874
Route package 5: Express Volda-Ålesund, Stryn, Nordfjordeid and Maurstad, +	01/01/2025	80	3,308,636
Route package 6: Express Kristiansund-Oppdal, Molde/Kristiansund - Trondheim	01/07/2026	80	2,234,027
Route package 7: Express Molde-Åndalsnes, local buses Rauma, Vestnes	01/01/2027	29	1,209,940
Route package 8: Local buses Eide, Fræna, Aukra, Midsund	01/01/2027	32	1,702,774

For each route package, a share of hydrogen buses was assumed, based on the date for the new contract start, and on the type of route (local vs. express bus). The total hydrogen demand was then calculated based on a consumption of 10 kg$_{H2}$/100 km. The hydrogen demand from buses in the county could start in 2024, and reach 237 tonnes$_{H2}$/year by 2027.

B6.3 HEAVY-DUTY VEHICLES

Heavy-duty vehicles registered in the Møre and Romsdal county drive on average 27,736 km per year (OFV, 2018). This is 22% lower than the average driven distances for these vehicles in the whole of Norway (35,565 km/year). This difference could be linked to the type of trucks and their driving patterns.

DNV GL (2019) indicates a hydrogen consumption of 9 kg$_{H2}$/100 km for heavy-duty vehicles. This is in line with a calculated consumption of 8.8 kg$_{H2}$/100 km based on the range and storage capacity of the Hyundai FC Truck (see also section A1.2). Combined with the average yearly distance driven, the consumption amounts to 2.5 tonnes$_{H2}$/year for trucks registered in Møre and Romsdal.

According to the registration statistics (Statistics Norway, 2019), there are 3,539 heavy-duty vehicles registered in the county, and 73,808 in Norway. The fleet registered in the county represent therefore 4.8% of the national fleet.

Estimates provided by DNV GL (2019) are 1,100 hydrogen heavy-duty vehicles nationally in 2025, and 5,000 in 2030. The respective shares are 1.5% of all trucks in 2025 and 6.8% in 2030. Assuming a homogeneous distribution in Norway, the fleet in Møre and Romsdal could reach 53 hydrogen heavy-duty vehicles in 2025 and 240 in 2030.

Based on these figures and assumptions, the yearly hydrogen demand from heavy-duty vehicles in Møre and Romsdal could reach 132 tonnes$_{H2}$/year in 2025 and 598 tonnes$_{H2}$/year in 2030.

B6.4 RAIL

The only railway in the county is the Rauma line (Raumabanen), which connects the town of Åndalsnes to the village of Dombås (Dovre Municipality in Oppland county). The line is 114 km long (NVES, 2018), and was used by both passenger trains and freight until the freight traffic stopped late 2018 (Åndalsnes Avis, 2018).

Figure 34 - Illustration of the Raumabanen. (photo: Leif J. Olestad)

NVES (2018) studied the potential for implementing hydrogen trains on the Rauma line, and estimated the hydrogen demand from the passenger trains to be in the range of 120 to 170 kg$_{H2}$/day total. This is equivalent to a yearly consumption of 39 to 55 tonnes$_{H2}$/year since the service is reduced during weekends.

NVES notes that the Coralia iLint hydrogen train (see also section A1.3) has a tank capacity of 120 kg$_{H2}$. This would mean that the train could have enough range to cover the Rauma line several times per day without needing a refill.

B6.5 OTHER MARITIME

Although the interest for use of hydrogen in the maritime sector has increased significantly in the last few years, the actual developments are uncertain at the moment. It is therefore challenging to assess the hydrogen demand in the county until 2030.

DNV GL (2018) evaluates that the first hydrogen ships could come in operation from 2021. Based on a techno-economic analysis, the company evaluated that hydrogen as a fuel would most realistically be implemented for newbuild passenger ships with a size under 9,999 GT. According to the study, there would be 56 hydrogen ships within the passenger segment in 2030 in Norway.

The company Havila has defined plans for implementation of hydrogen technology on four of its Kystruten newbuilds (Havyard, 2018). DNV GL (2019) estimated a potential hydrogen demand of 2,000 tonnes per ship. However, the implementation will most likely happen gradually, and DNV GL estimated that the total demand in 2030 would be equivalent to only one ship consumption (i.e. 2,000 tonnes$_{H2}$/year), potentially shared over several ships.

Assuming that Havila would start fueling hydrogen in 2023, and that between one and two thirds of the demand could be fueled in Møre and Romsdal (low and high case), the local hydrogen demand from Havila could reach 667 to 1,333 $tonnes_{H2}$/year.

Hydrogen could be relevant for other passenger ships in the county. The lines Hareid-Valderøya-Ålesund, Langevåg-Ålesund and Molde-Vestnes-Sekken are however considered to be too short for hydrogen, and would most likely be electrified. Hydrogen could be suitable for the Ålesund-Valderøya-Nordøyane line, which is 37 nm long and has a crossing time of ca. 1 hour and 25 minutes. This line has roughly 52 trips per week. The equivalent hydrogen consumption would be ca. 380 tonnes/year, based on an average consumption of 3.8 kg_{H2}/nm. The current contract for this line expires in 2027, unless a two-years option is implemented (Statens vegvesen, 2019). The potential hydrogen demand from this ship would therefore be relevant from 2027 at the earliest.

B6.6 INDUSTRY

Hydrogen is commonly used in the chemicals and petrochemicals industry as a raw material to products such as methanol and ammonia, and as input to the treatment of petroleum products in refineries.

In Møre and Romsdal, the Tjeldbergodden plant operated by Equinor converts natural gas to hydrogen for producing methanol. The plant has a production capacity of ca. 900,000 tonnes methanol per year (Equinor, 2019), which is equivalent to ca. 112,000 tonnes hydrogen per year. Large facilities such as Tjeldbergodden have their own methane reforming facilities for producing hydrogen and would not be a relevant customer for hydrogen from Smøla. There are currently no known other hydrogen uses for the industry in the county.

The Norwegian construction and civil engineering company Veidekke is studying the potential to use hydrogen at its asphalt plant in Kristiansund (TU, 2019). The company has initiated contacts with Equinor to investigate the possibility to procure hydrogen from the Tjeldbergodden industrial facility, although hydrogen made from electrolysis at other locations is also a considered option. There are ongoing debates related to the fact that hydrogen from Tjeldbergodden is produced through natural gas reforming, which leads to significant CO_2 emissions. This hydrogen is therefore far from being emission-free when seen on a life-cycle perspective. Equinor mentions the potential for carbon capture and storage at the plant, although the company asks for the possibility to provide hydrogen produced without this technology in the short to medium term (TU, 2019b).

Hydrogen is relevant as a fuel or input factor for few industries, but the required consumption is typically high and local production would therefore likely be preferred (DNV GL, 2019). In addition, the potential hydrogen demand from Veidekke and other industrial uses in the county is unknown at the moment, and these are therefore not included in this report.

The hydrogen demand in Møre and Romsdal county could start as soon as 2021-2022 with a limited number of cars and heavy duty vehicles. By 2030, the maritime sector, trucks and cars could make-up most of the demand. The estimated total demand is 1,546 tonnes$_{H2}$/year for the low case, and 3,473 tonnes$_{H2}$/year for the high case, as illustrated below.

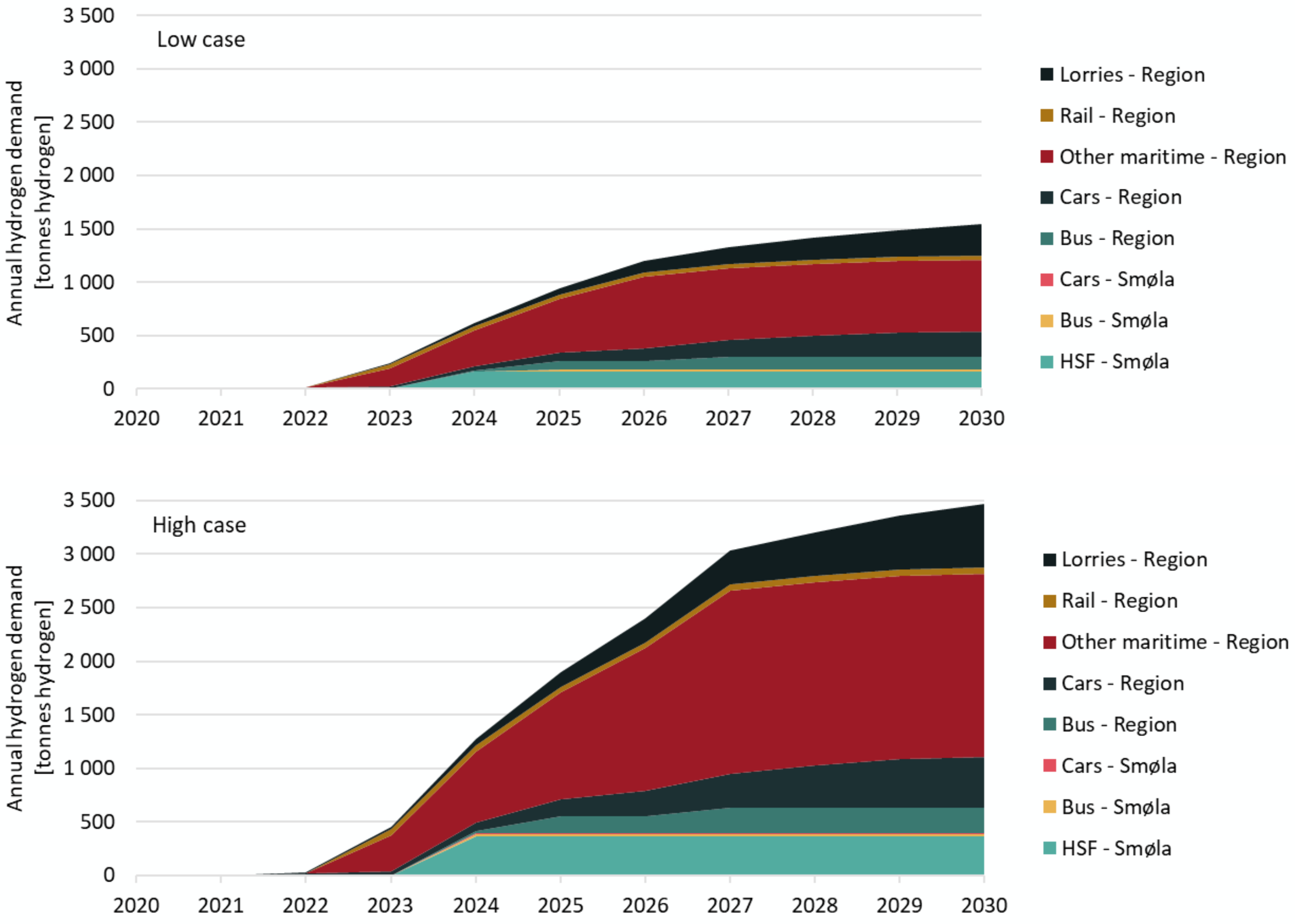

Figure 35 - Evolution of the estimated hydrogen demand in Møre and Romsdal until 2030. Top: low case. Bottom: high case

It should be noted that the estimates come with uncertainties linked to the development of technologies within the different market segments studied. In addition, the industrial demand for hydrogen is not included in this assessment (see also section B6.6).

When focusing on Smøla, no demand is expected before 2024. It is clear that the high speed ferries make most of the hydrogen demand already in 2025 (high case), and still in 2030.

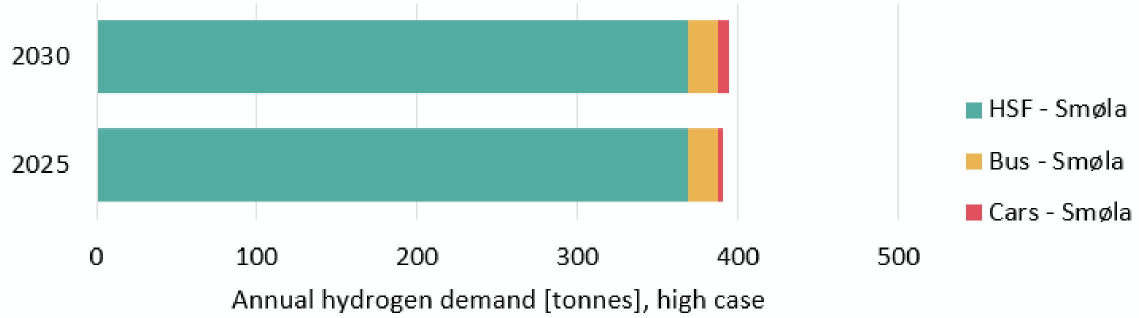

Figure 36 - Estimated hydrogen demand at Smøla 2025 and 2030

For the rest of the county, there is very little demand by 2022, and the maritime sector make most of the demand in 2030, as illustrated in the figure below (note the difference in scale with the figure above).

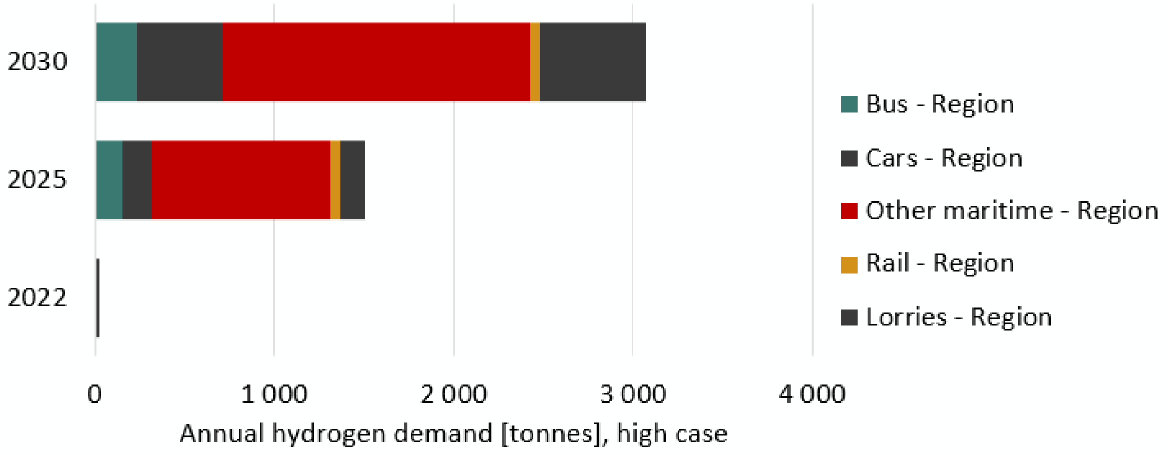

Figure 37 - Estimated hydrogen demand in the rest of the county in 2022, 2025 and 2030

B8 LOCATION OF THE DEMAND

The demand would be spread over the whole county, with significant amounts at hubs such as Ålesund, Molde and Kristiansund. Because of the distances and transport costs involved, however, not all of the demand in the county is relevant for distribution from Smøla. The chart below illustrates the distances and travel times for some of the main cities in the region.

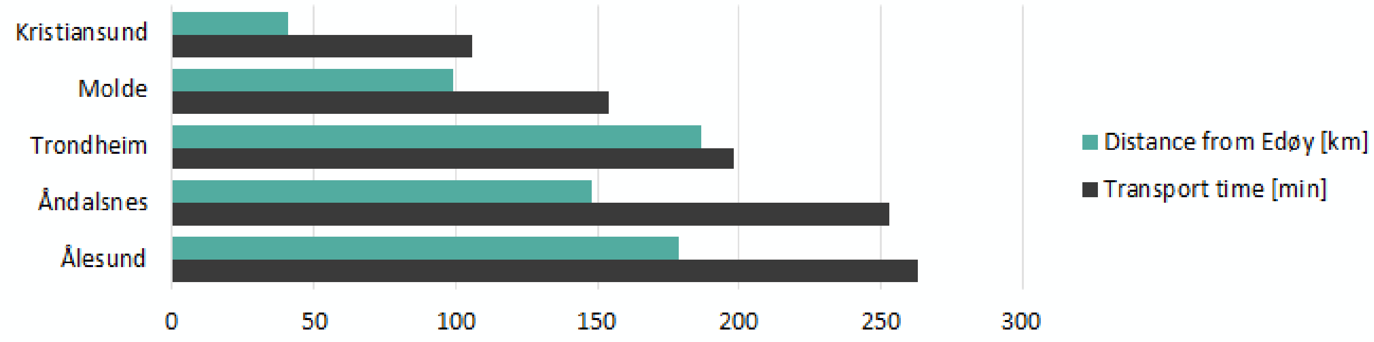

Figure 38 - Distances and transport time from Edøy to main cities in the region

Demand located in a radius up to Molde and Åndalsnes is considered relevant for this project. This includes Kristiansund, but does not include potential demand in the neighboring county, Trøndelag, due to scope limitations. There will most likely be significant hydrogen demand in the future in Trondheim and other areas in Trøndelag, and this should be considered in a future potential assessment.

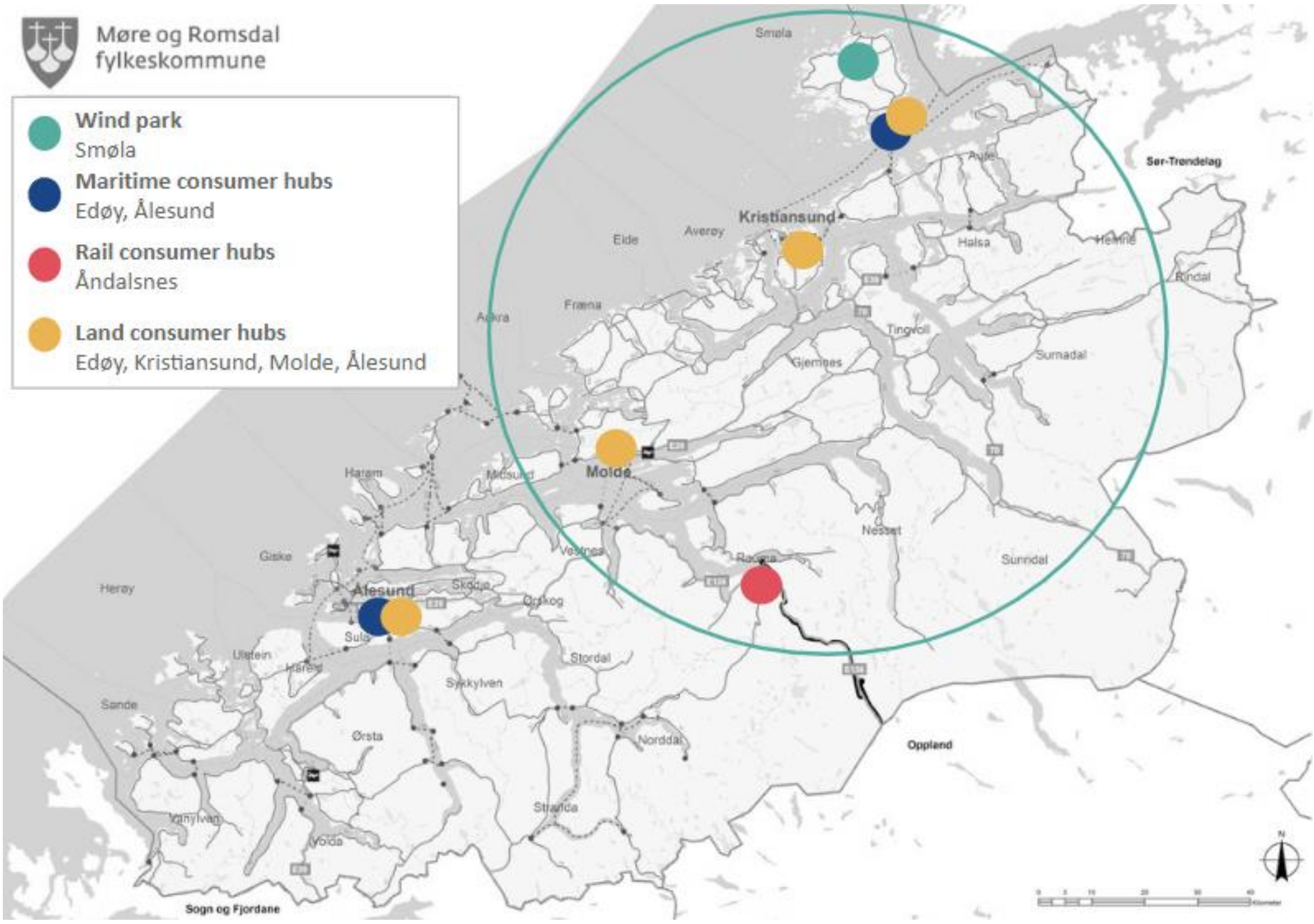

Figure 39 - Location of the main consumer hubs in the county, and radius for the relevant demand for this project (green circle)

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APPENDIX C - SUPPLY ANALYSIS

C1. PRE-SELECTION OF THE CONCEPTS

A total of five concepts were studied as part of this project, and two were selected for further assessment. The table below shows an overview of the concepts.

Table 3 - Overview of the concepts studied in the project

Concept #	Production and storage	Transport	Distribution
1	At the wind park, storage in containers on wheels	Truck transport to the consumers, with containers on wheels	At Edøy quay, to high speed ferries and buses
2*	At Edøy, storage in containers on wheels	No truck transport needed	At Edøy quay, to high speed ferries and buses
3	At the wind park, storage in containers on wheels	Truck transport to the consumers, with containers on wheels	At Edøy quay, to high speed ferries and buses Distribution to regional consumers (trucks, cars, train)
4	At Edøy, storage in containers on wheels	No truck transport needed	At Edøy quay, to high speed ferries and buses Distribution to regional consumers (trucks, cars, train)
5*	At Vikan, storage in containers on wheels	Truck transport to the consumers, with containers on wheels	At Vikan to potential local user (fish farming, industry) At Edøy quay, to high speed ferries and buses

** Concepts selected for further assessment.*

In general, solutions with production at the wind park (# 1 and 3) are expected to have a cheaper production cost since the grid fee (*nettleie*) is avoided. However, these solutions do not have an immediate local use of hydrogen, oxygen or heat, since there are only wind turbines at the wind park. Significant transport is therefore required, which adds costs to these solutions.

On the other hand, solutions with production outside of the park, at Edøy or Vikan (# 2, 4 and 5), make it possible to reduce the transport needs, but lead to higher energy costs due to the grid fee. In addition, these solutions may require an upgrade of the local grid, which could lead to additional fees (*anleggsbidrag*).

The five concepts were evaluated against each-other during a workshop with participants from the project team, Møre and Romsdal county, NVES, Smøla municipality and other local stakeholders. When asked to rank the most important criteria for the project, the participants provided the following five in order of preference:

- Contribution to a low-emission society (national goal for 2050),
- Realistic concept (i.e. technically feasible, enough demand),
- Profitable solution,
- Value-creation for the local community and with regional added benefits,
- Net emission reductions.

These criteria were used to select concepts #2 and 5 for further assessment. The concepts are described further in detail in the next section and are further referred to as Case A and Case B.

C2. CASE DESCRIPTION AND ASSESSMENT

With both cases the main purpose is to provide hydrogen for the high speed ferries located at Edøy (site 1 on the map below). Case A groups the production and distribution at Edøy, while case B has production at Vikan (site 2 on the map), and distribution at Edøy.

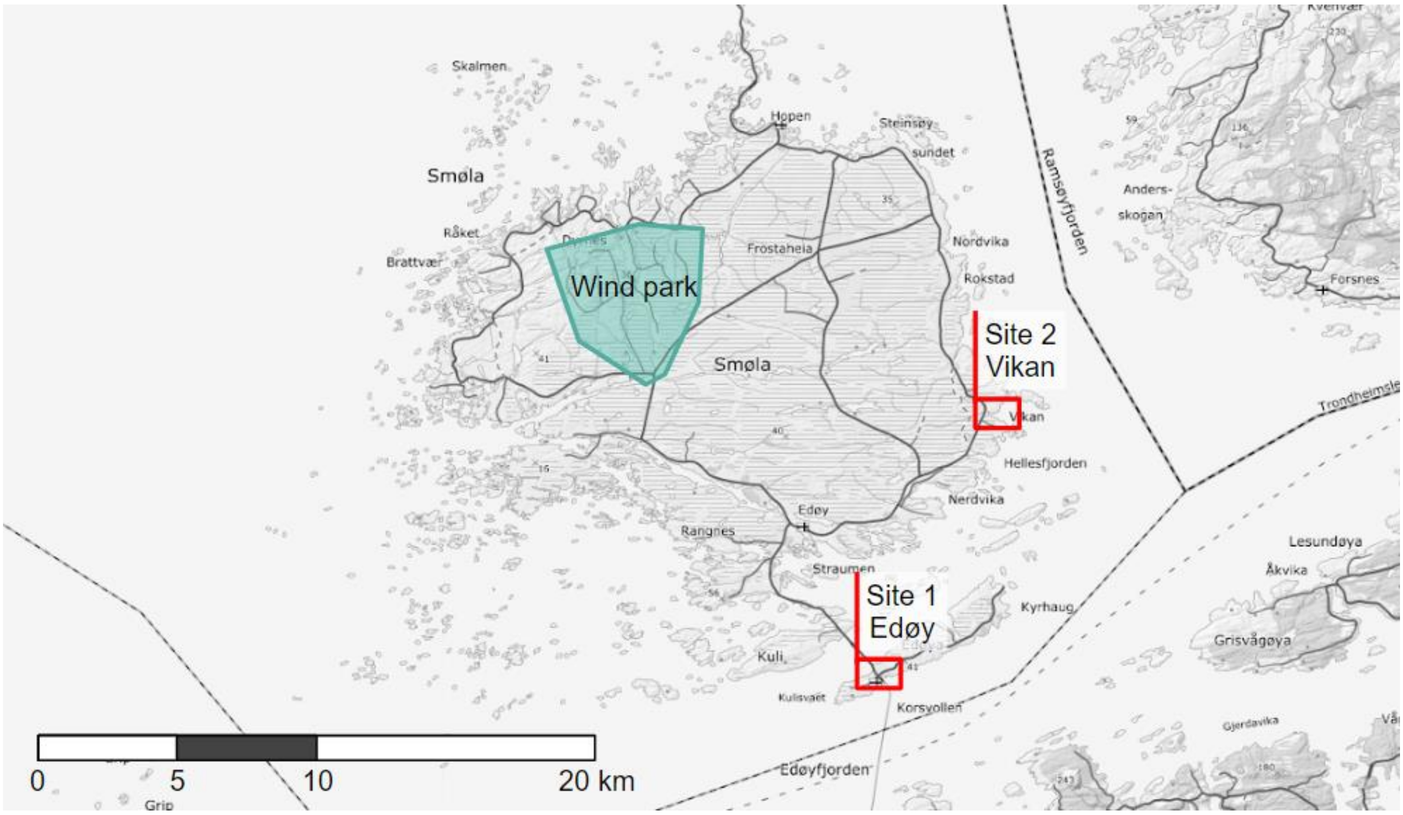


Figure 40 - Location of the two sites for production and distribution of hydrogen, and of the wind park at Smøla

It should be noted that some of the specifications for the two cases are based on technology currently being developed, and that the actual performance will depend on the status of technology development when the project is implemented. This is in particular applicable for the filling speed assumed for the dispensers.

C2.1 CASE A

C2.1a Case A - Technical description

Case A has a production capacity of 1.049 tonnes$_{H2}$/day located at Edøy. An empty lot at Nausthaugen has been identified as a potential site for the production equipment (see map below). The electrolyzer and associated utilities would be installed in an industrial building to be built on the site.

The following equipment would be included at the production site:

- Electrolyzer with 1.049 tonnes$_{H2}$/day capacity (NEL A485 or equivalent),
- Utilities: transformer, rectifier, scrubber water systems, etc.,
- Hydrogen buffer tank.

The total required area at the production site is estimated to be ca. 769 m^2, including a building of 245 m^2 for housing of the electrolyzer and main equipment. This includes assumed safety distances (uncertain).

Low pressure hydrogen will be transported via pipeline to the high pressure compressors to be installed in proximity to the quay (see map below). Although available land is limited at that location, Smøla indicated that it is possible to reclaim land over the sea as it was already done for building a resting house for the ferry personnel. Two high pressure compression systems will be installed, for redundancy. Compressors are typically less reliable than other equipment, and the redundancy will allow making sure that the hydrogen supply to the high speed ferries is not limited by potential malfunctions. In addition, high pressure storage tanks with a capacity of 2.1 tonnes$_{H2}$ at 350 bar will be installed next to the compressors. The equipment is expected to require a total surface area of ca. 127 m^2, including assumed safety distances.

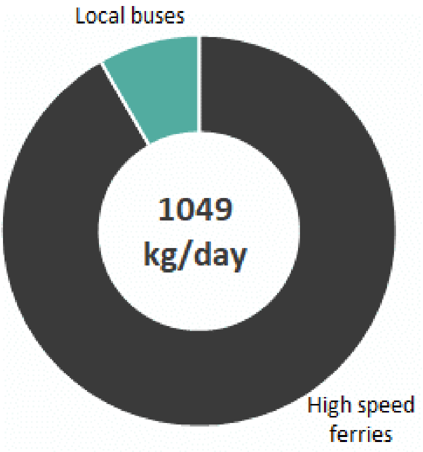


Figure 41 - Hydrogen users with Case A

Finally, high pressure hydrogen will be sent to the dispensers through a shorter pipeline under the quay. There will be two dispensers for the high speed ferries, in order to ensure a high filling rate. There will also be one dispenser for the buses. A total of ca. 46 m^2 is required at the quay for the dispensers.

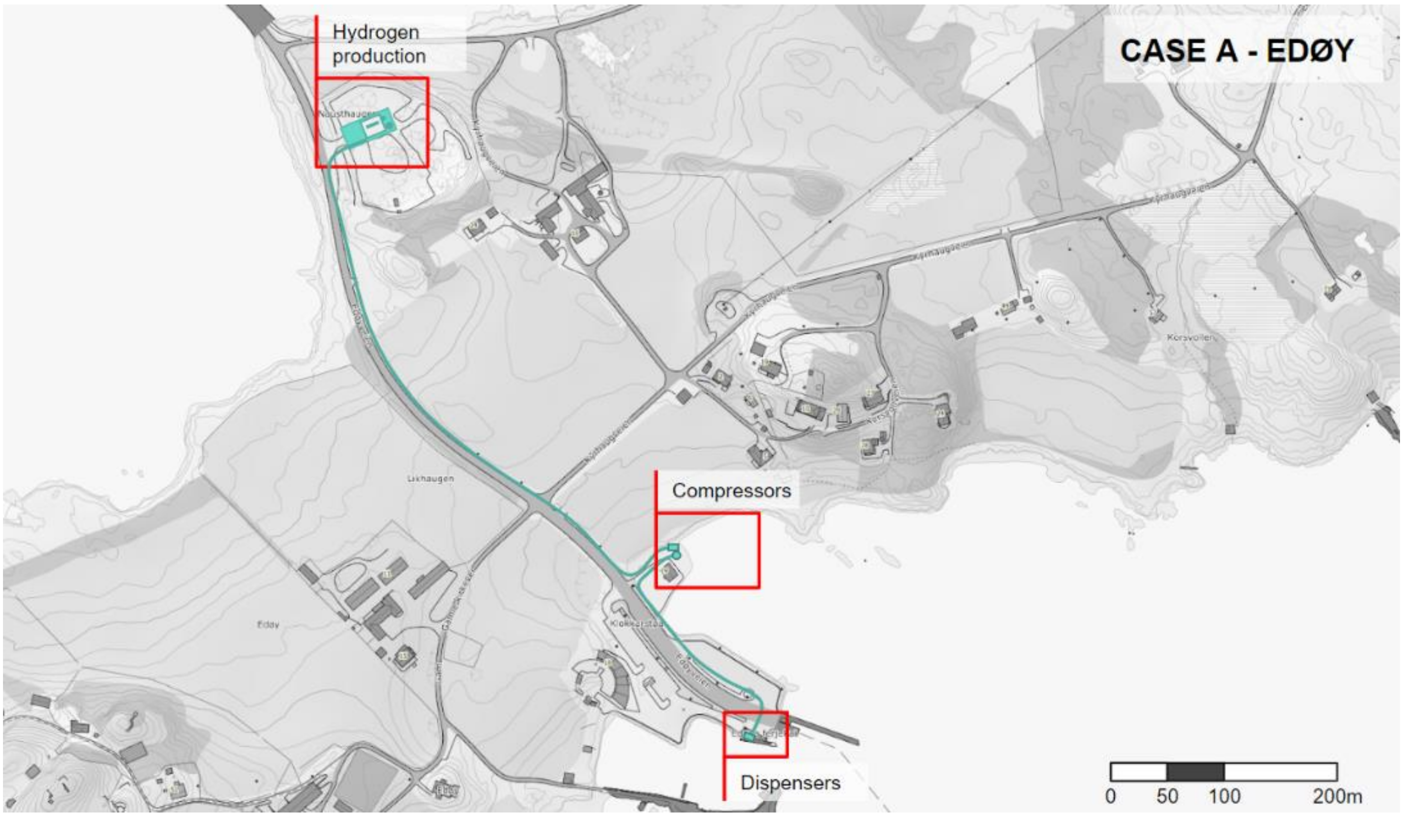


Figure 42 - Map with the location of the main equipment for case A at Edøy (dimensions are approximate)

The use of neither oxygen nor heat as by-products of the hydrogen production are included in case A. No significant users for these products were identified in the close proximity of the production site at Edøy. Oxygen could theoretically be compressed or liquefied and transported to local or regional users. However, transport of compressed oxygen is both expensive and challenging (linked to the transport of dangerous goods regulation, *ADR*) (pers. comm. with T. Fiksdal, Greenstat). In addition, oxygen liquefaction is costly. Therefore, Case A does not include a valorization of the oxygen or heat produced.

The main technical characteristics of case A are summarized in the table below.

Table 4 - Main technical characteristics of case A

System	Equipment	Main characteristics
Hydrogen production	Electrolyzer (NEL A485 or equivalent)	● 1.049 tonnes_{H2}/day production capacity ● 3.8-4.4 kWh/Nm^3 DC power consumption ● 0.9 l/Nm^3 water consumption ● 80ºC operating temperature
	Hydrogen buffer tank	● capacity and pressure to be determined
Pipeline to compressors		● 20-30 bar pressure ● 600 m long ● 100 mm diameter
High pressure compression and	Compressors	● 2 x compression system ● 30 to 350 bar compression

storage	High pressure storage	● 2.1 tonnes$_{H2}$ storage ● 350 bar pressure
Pipeline to dispensers		● 350 bar pressure ● 150 m long
Dispensers	Dispensers for high speed ferries	● 250 bar pressure ● 22.5 kg/min max filling rate
	Dispenser for buses	● 250 bar pressure

C2.1b Case A - Economic assessment

Investment cost figures were collected based on the main technical characteristics described in the table above. HYON is the main source for the cost figures, along with other sources such as NVE (2017), NVES (2018, 2019), NEL (2017) and Reddi et al. (2016). The Smøla Municipality provided estimates for the estate costs in the area. The figure below summarizes the main CAPEX elements. This is a relatively rough assessment of the CAPEX since both cases are concepts.

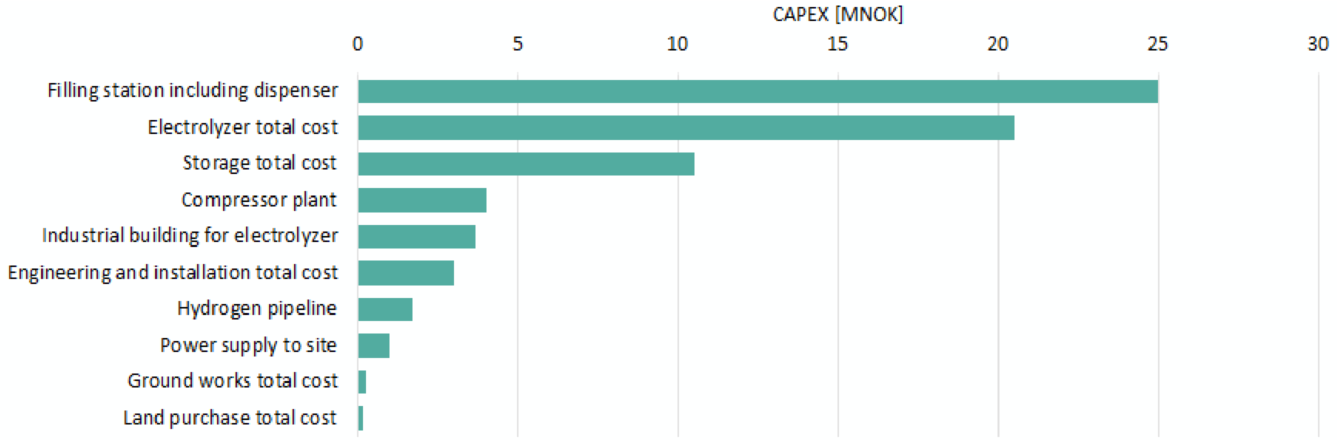


Figure 43 - CAPEX elements for case A

The total CAPEX for case A is estimated to 69.8 million Norwegian kroner. The filling station, the electrolyzer and the storage equipment make up the largest share of the CAPEX. Significant investments are also required in terms of compressor plant, engineering and installation, and for the industrial building housing the electrolyzer.

With regards to operational costs (OPEX), figures are provided by HYON and NVE (2017). The figure below summarizes the OPEX for case A.

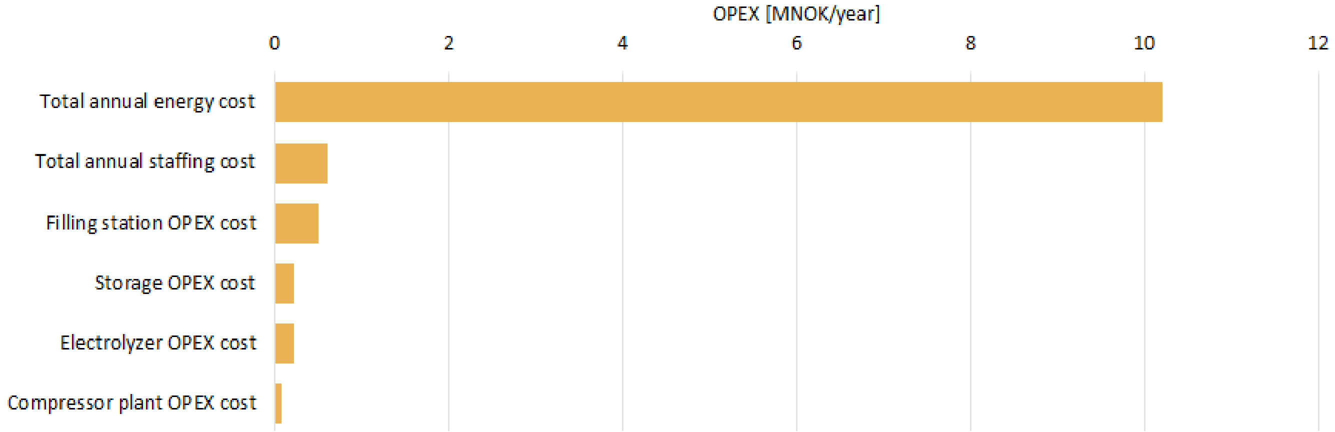


Figure 44 - OPEX elements for case A

Energy costs make the largest share of OPEX, by far. For case A, an electricity cost of 0.45 NOK/kWh is assumed, based on input from NVES (2019). It should be noted that regeneration of the electrolyzer is included in the CAPEX and not in the OPEX figures.

The main revenues for case A would be hydrogen sales. There are no heat or oxygen users in the close proximity of the hydrogen production with this case, and therefore no value is attributed to heat nor oxygen.

Revenues for case A are summarized in the figure below, based on a break-even hydrogen price at 47.3 NOK/kg.

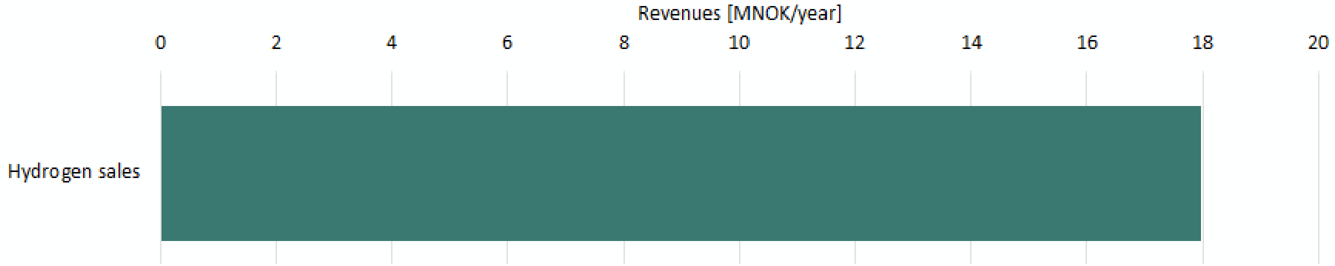


Figure 45 - Revenues with case A, assuming a hydrogen price at 47.3 NOK/kg

C2.2 CASE B

2.2a Case B - Technical description

Case B has a production capacity of 2.1 tonnes$_{H2}$/day located at Vikan. The Smøla municipality is currently preparing the site at Vikan for industrial activities, and has reserved a lot for hydrogen production (see map below). The electrolyzer and associated utilities would be installed in an industrial building to be built on the site.

The following equipment would be included at the production site:

- Two electrolyzers with 1.049 tonnes$_{H2}$/day capacity each (NEL A485 or equivalent),
- Utilities: transformer, rectifier, scrubber water systems, etc.,
- Compressors,
- Hydrogen buffer tank,
- Heat recovery equipment,
- Oxygen equipment.

Hydrogen is to be stored in high pressure containers on wheels, near the production site, for transport to the consumers at Edøy and in the region. In addition, the case includes the possibility for a hydrogen pipeline to a dispenser at the quay at Vikan, for potential consumers there, although this equipment is not included in the assessment.

With case B, the heat and oxygen byproducts are recovered and used for a potential nearby fish hatchery. There are no confirmed plans for installation of a hatchery at the moment, but for simplification purposes the rest of this assessment will assume that there will be a local user for the heat and oxygen at Vikan.

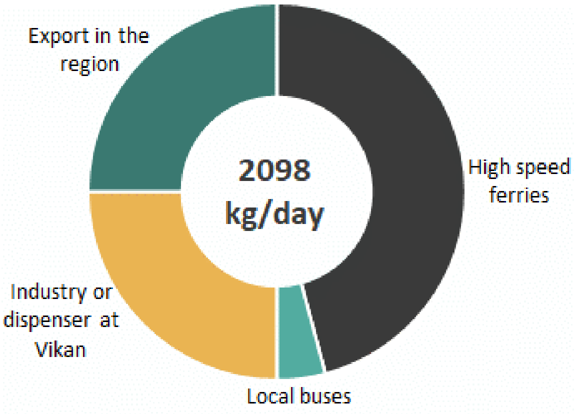


Figure 46 - Hydrogen users with Case B

Equipment is needed in order to recover heat from the hydrogen production: heating medium system (tank, pumps), exchangers, piping system from the hydrogen production site to the heat user. It was estimated that ca. 1.3 MW heat could be recovered from the hydrogen production and used by the potential nearby fish hatchery. It should be noted that the heat demand would typically vary on a seasonal basis (NVE, 2017). For this assessment, it is assumed that there is enough demand for 1.3 MW on average throughout the year. The price for heat is uncertain, and 0.2 NOK/kWh$_{heat}$ was used in this assessment. This represents ca. one third of heat prices from district heating in Norway, or of the potential heat cost from installation and use of electric boilers (based on Endrava's own calculations).

Oxygen is assumed to be only used locally, due to the high cost and safety complexities of compression or liquefaction (see also case A). A total of 16.8 tonnes oxygen would be produced daily and could be used by the hatchery. Based on an oxygen demand of 0.5 tonnes$_{O2}$/tonnes fish (NVE, 2017), this corresponds to the demand of a hatchery with ca. 12,000 tonnes fish produced yearly. The oxygen would be transported at low pressure directly to the hatchery through a pipeline. The oxygen price is assumed to be 2 NOK/kg$_{O2}$ (NVE, 2017).

The total required area at the production site is estimated to be ca. 1,372 m^2, including a building of ca. 408 m^2 for housing of the electrolyzer and main equipment. This includes assumed safety distances (uncertain).

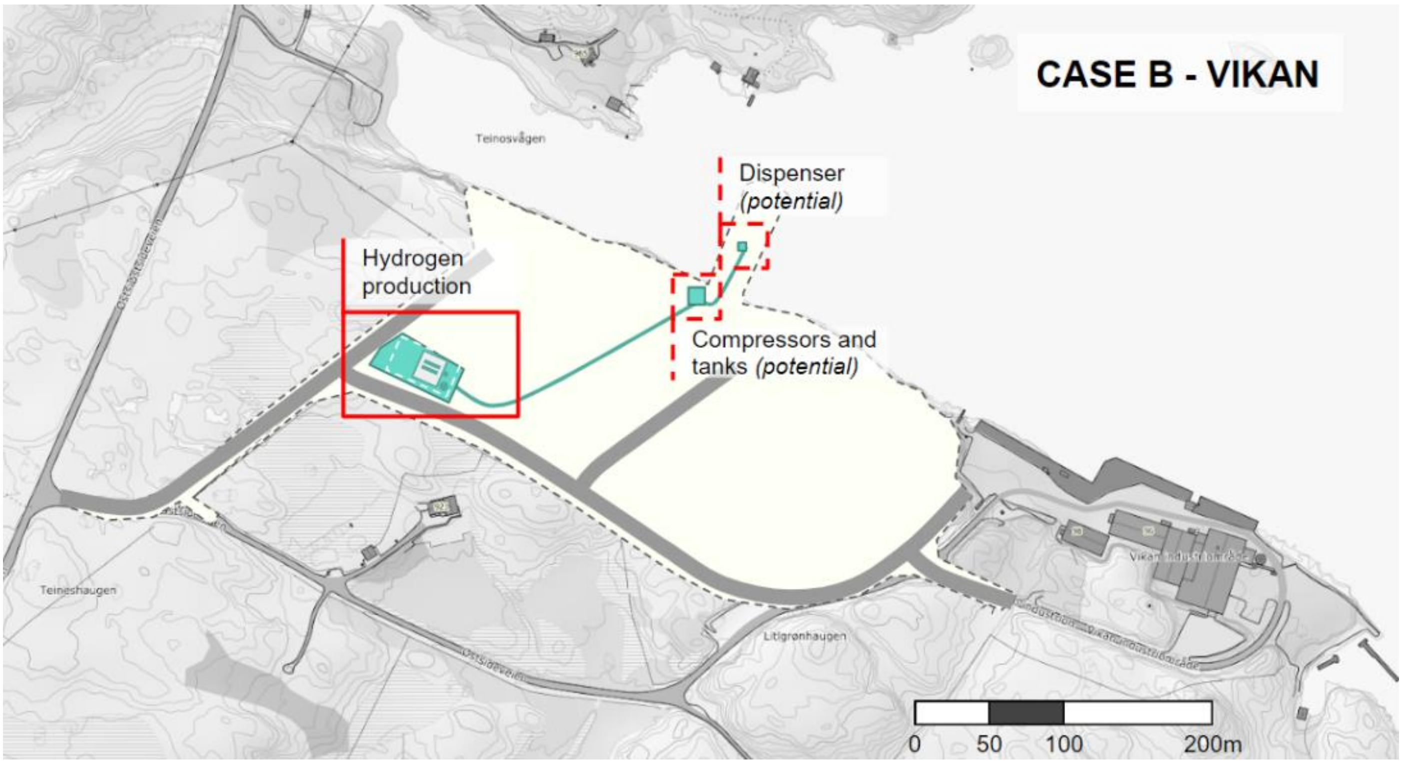


Figure 47 - Map with the location of the main equipment for case B at Vikan (dimensions are approximate)

Most of the hydrogen demand with case B is expected to be located at Edøy. High pressure hydrogen will be transported by truck in containers on wheels. One container will be located at Edøy. There will be two dispensers for the high speed ferries, in order to ensure a high filling rate. There will also be one dispenser for the buses. A total of ca. 121 m^2 is required at the quay for the dispensers and the hydrogen container on wheels. This includes assumed safety distances (uncertain).

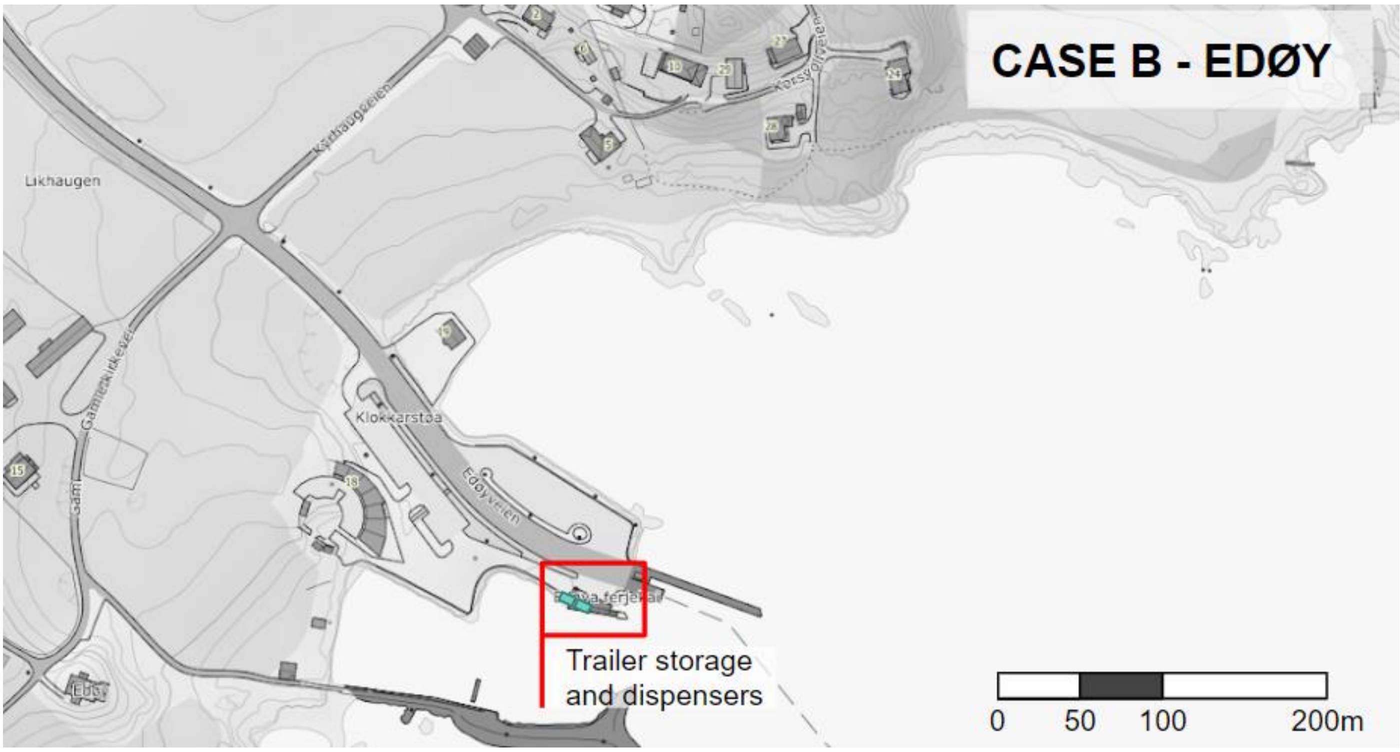


Figure 48 - Map with the location of the distribution equipment for case B at Edøy (dimensions are approximate)

The main technical characteristics of case B are summarized in the table below.

Table 5 - Main technical characteristics of case B

System	Equipment	Main characteristics
Hydrogen production	Electrolyzer (NEL A485 or equivalent)	• 2.1 tonnes$_{H2}$/day total production capacity • 3.8-4.4 kWh/Nm^3 DC power consumption • 0.9 l/Nm^3 water consumption • 80ºC operating temperature
	Hydrogen buffer tank	• 2.1 tonnes$_{H2}$, pressure to be determined
Heat recovery and oxygen*	Heating medium system (tank, pumps), exchangers, piping system	• 1.3 MW heat recovery
	Oxygen pipeline	• length and pressure to be determined • 16.8 tonnes$_{O2}$/day capacity
High pressure compression and storage	Compressors	• 2 x compression system • 30 to 350 bar compression
	High pressure storage	• 6 tanks on trailer total (on filled, one in transport, two at users) • 0.8 tonnes$_{H2}$ storage each • 350 bar pressure
Dispensers	Dispensers for high speed ferries	• 250 bar pressure • 22.5 kg/min max filling rate
	Dispenser for buses	• 250 bar pressure

** equipment for heat recovery and oxygen are not included in the economic assessment.*

C2.2b Case B - Economic assessment

Investment cost figures were collected based on the main technical characteristics described in Table 5 above. Similarly to Case A, HYON is the main source for the cost figures, along with other sources such as NVE (2017), NVES (2018, 2019), NEL (2017) and Reddi et al. (2016). The Smøla Municipality provided estimates for the estate costs in the area. The figure below summarizes the main CAPEX elements. This is a relatively rough assessment of the CAPEX since both cases are concepts. It should be noted that the cost related to heat and oxygen recovery equipment are not included in the assessment since they are assumed to be covered by the potential industrial site using these byproducts.

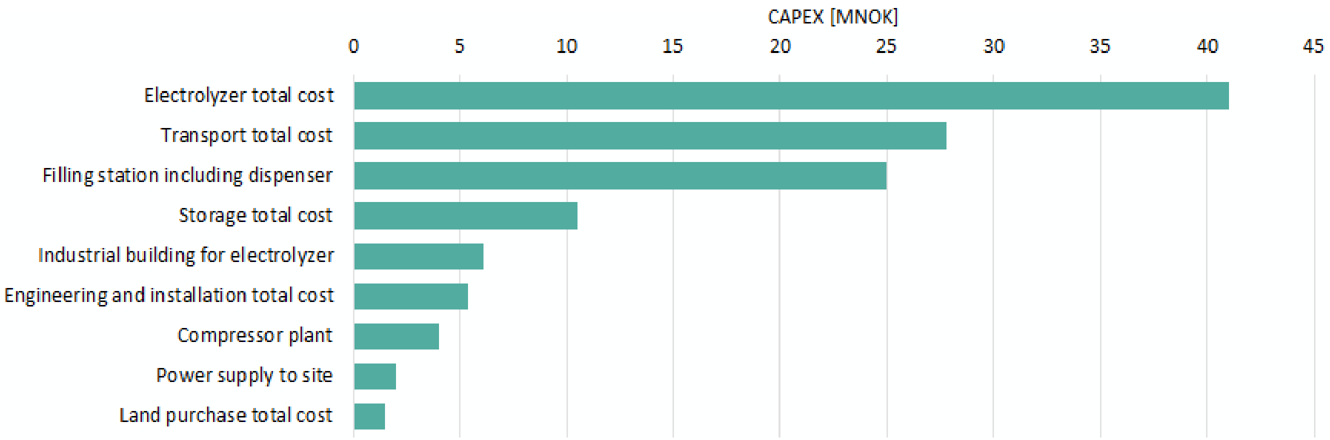


Figure 49 - CAPEX elements for case B

The total CAPEX for case B is estimated to 123.3 million Norwegian kroner. The electrolyzer, the transport equipment (truck and storage on wheels), and the dispenser make up the largest share of the CAPEX. Significant investments are also required in terms of buffer storage, engineering and installation, and for the industrial building housing the electrolyzer.

With regards to operational costs (OPEX), figures are provided by HYON and NVE (2017). The figure below summarizes the OPEX for case B.

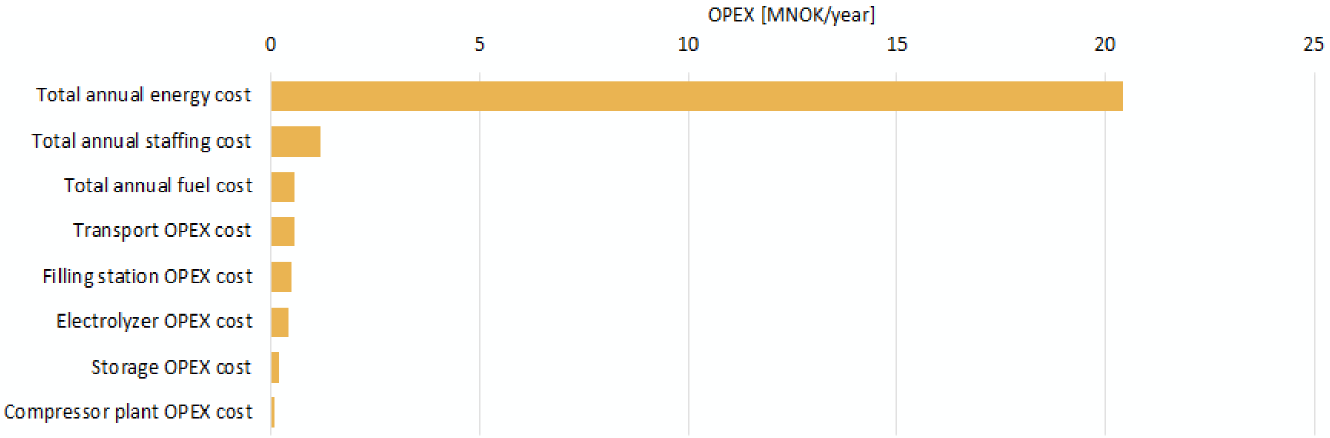


Figure 50 - OPEX elements for case B

Energy costs make the largest share of OPEX, by far. For case B, an energy cost of 0.45 NOK/kWh is assumed, based on input from NVES (2019). It should be noted that regeneration of the electrolyzer is included in the CAPEX and not in the OPEX figures.

The main revenues for case B would be hydrogen sales. Oxygen and heat sales (to a lesser degree) also make a significant share of revenues for this case. This is based on the assumption that a nearby hatchery would be set-up at Vikan, and would need the totality of the heat and oxygen produced. This assumption is optimistic, since the demand would vary throughout the year. The heat demand in particular is expected to be reduced during the summer months, depending on the seasonal temperatures (NVE, 2017).

Revenues for case B are summarized in the figure below, based on a break-even hydrogen price at 27.0 NOK/kg, oxygen price at 2 NOK/kg, and heat price at 0.2 NOK/kWh.

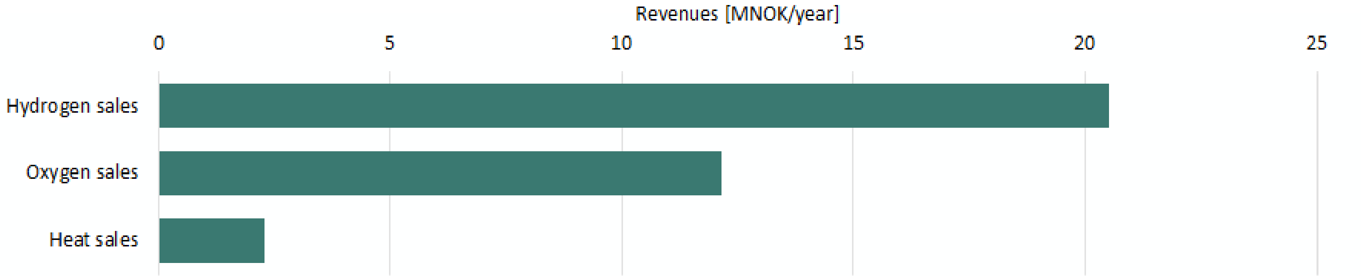


Figure 51 - Revenues with case B

With case B, oxygen also makes a significant part of the revenues, in addition to hydrogen sales. Heat sales, on the contrary, make only a minor contribution. The revenues from both oxygen and heat make it possible to obtain lower a hydrogen break-even production cost, when compared to case A, as presented in the comparison below.

C3. CASE COMPARISON

C3.1 KEY ECONOMIC FIGURES

The figure below summarizes the key economic figures for case A and case B.

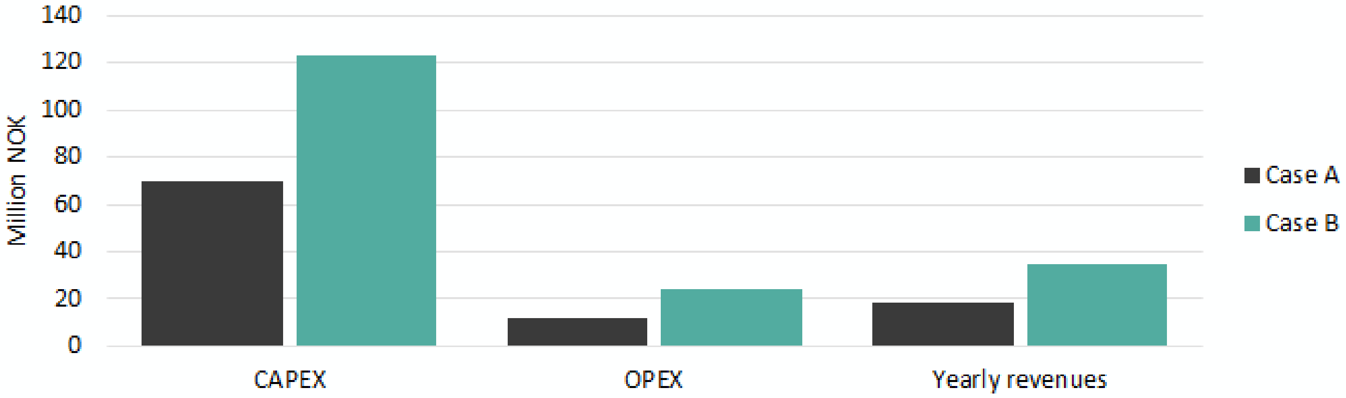


Figure 52 - CAPEX, OPEX and yearly revenues for both cases

Due to its higher production, Case B requires high investments (CAPEX), involves higher operational expenditures (OPEX), but also brings more yearly revenues.

The economics of case A and B lead to break-even hydrogen production prices at 47.3 and 27.0 NOK/kg$_{H2}$, respectively. Figure 53 presents the contribution of different cost elements to the production costs. Note that the costs are discounted over the project period (20 years of operation, 7% discount rate).

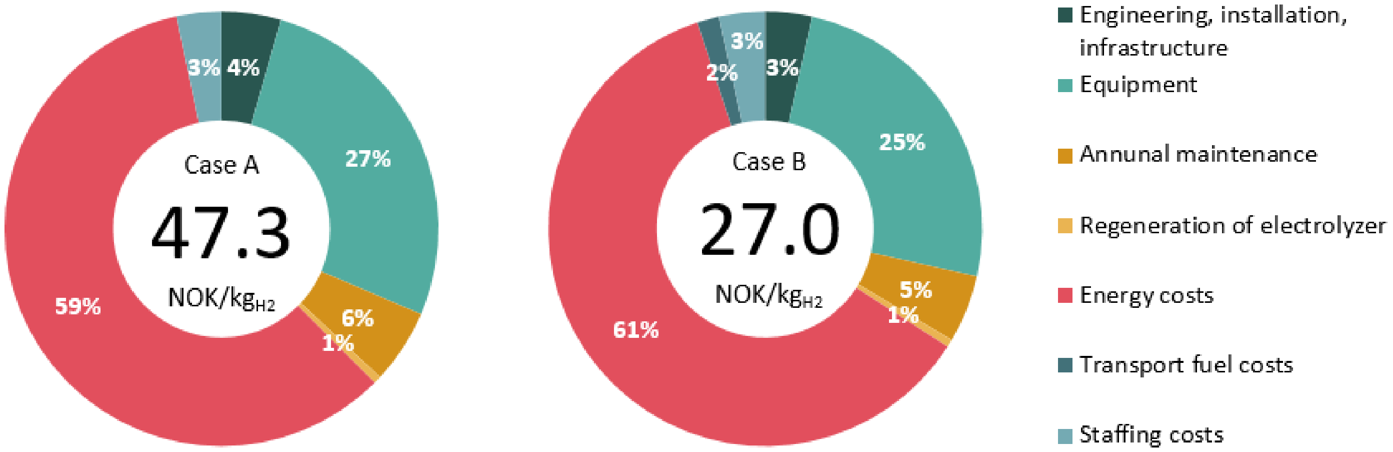


Figure 53 - Break-even price and contributors to the production cost for case A and case B (discounted over the project period)

On the overall, the main contributors are the same for both cases: energy costs contribute to the largest share of production costs, with 59% for case A, and 61% for case B (discounted over the project period). The second largest contributor is equipment, with 27% for case A and 25% for case B.

These results confirm the importance of energy costs for hydrogen production from electrolysis. Variations in energy costs can lead to large variations in break-even price and the profitability of the project. It should be noted that electrolyzers become less efficient over time and their energy use therefore increase with the years, at stable production output. In this modelling, a factor of 1% annual efficiency decrease was included, as well as a regeneration of the electrolyzer after 10 years of operation.

Both cases A and B require changes to the local electricity grid. Detailed information became available at the end of the project and the elements described below are therefore not included in the economic assessment.

NEAS, the local grid operator, indicated that Case A at Edøy would require the installation of a larger transformer station at Nordheim, a local cable and facility. The total costs would add-up to ca. 2 to 2.5 MNOK.

Changes to the grid for Case B are more comprehensive than for Case A since the local grid does not currently allow for much larger power requirements. It would include a new cable (6-7 km in marsh landscape, 5-9 km of aerial lines), changes to the transformer station, and a new local facility. This would add-up to ca. 17.5 MNOK, and half of it could be relevant for the hydrogen production and the other half for local industries.

Although these investment figures are significant in absolute terms, they are relatively limited compared to the total investments for the project (see also Figure 52). In practice, investments in grid modifications would increase the hydrogen production costs by ca. 0.7 NOK/kg_{H2}.

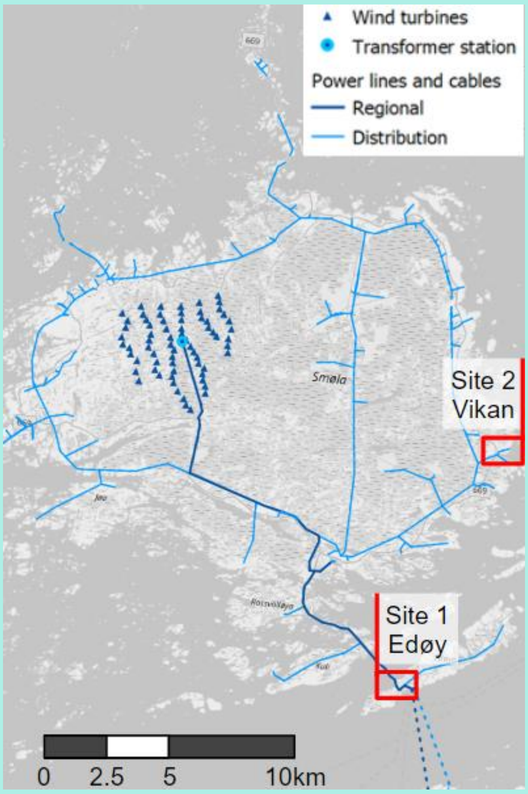


Figure 54 - Project sites, wind park and power lines on Smøla

C3.2 SENSITIVITY ANALYSIS

Each of the factors and assumptions used in the economic analysis have an influence on the hydrogen break-even price. This section presents a sensitivity analysis for some of the parameters used in the calculations.

Electricity costs are the main contributor to the hydrogen production cost, and therefore have a large influence on the break-even price, as illustrated in the figure below.

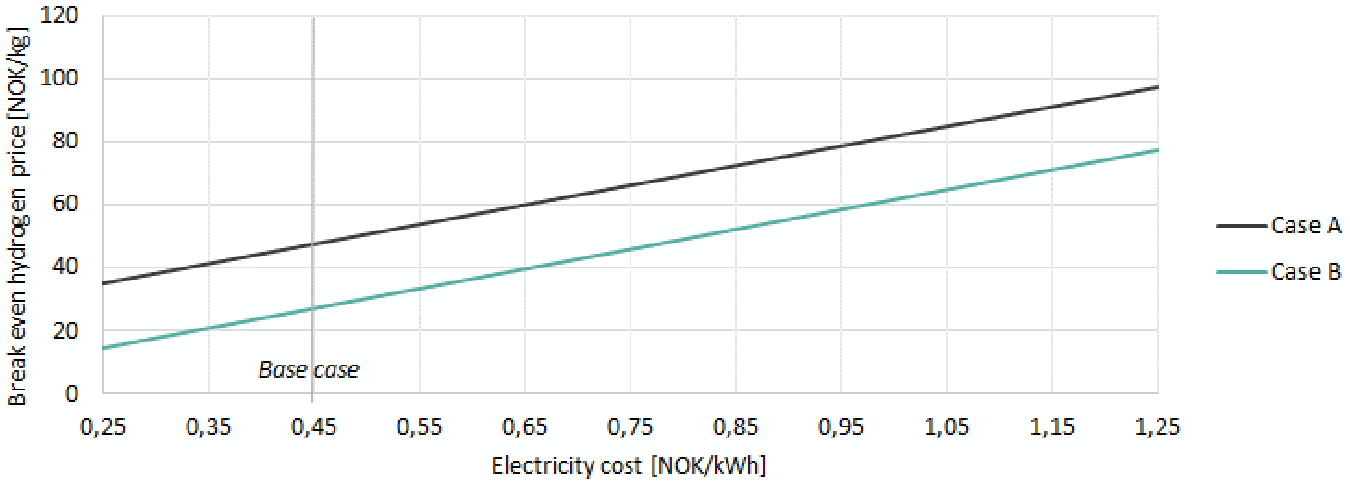


Figure 55 - Break-even hydrogen price as a function of electricity costs for case A and B

A potential doubling of the electricity costs, from 0.45 NOK/kWh to 0.9 NOK/kWh, would lead to an increase of 28 NOK/kg$_{H2}$ for the break-even hydrogen price.

The performance curve of electrolyzers is almost linear, which means that their electricity use is almost directly proportional to their production output (Guandalini, 2015). In this project, a fixed consumption factor of 60 kWh/kg$_{H2}$ was used for the electrolysis and hydrogen compression to 350 bar. This corresponds to an overall energy efficiency of 56% (compression included, ca. 64% without compression). A decrease in the production from the electrolyzer would therefore lead to a proportional decrease in the energy use and cost. The resulting effect on the break-even hydrogen price is illustrated in the figure below.

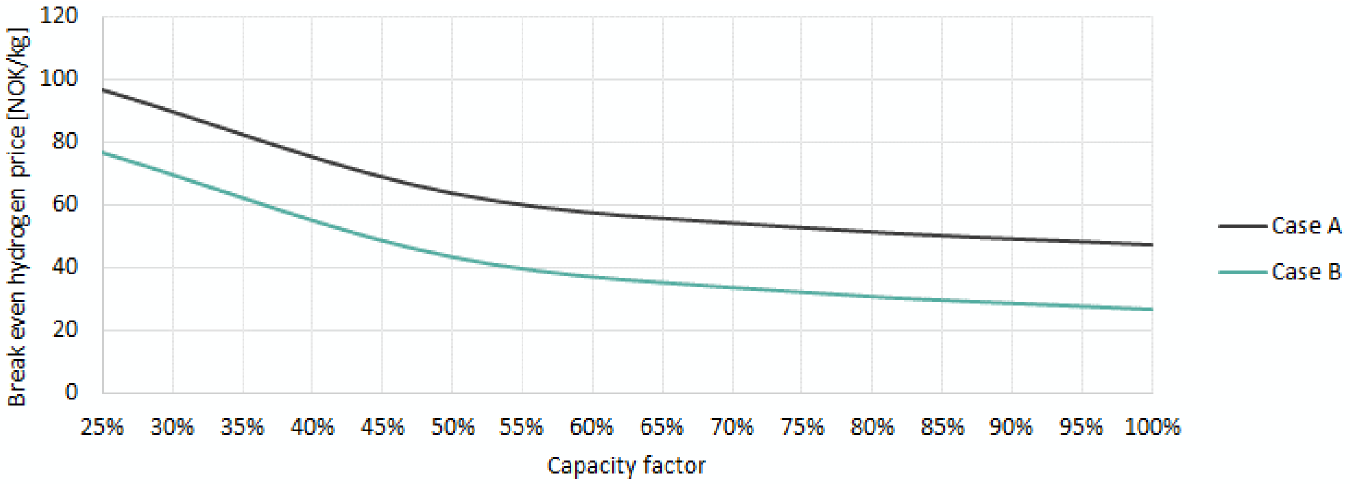


Figure 56 - Break-even hydrogen price as a function of capacity factor for case A and B

Running the production at lower capacity has moderate effects on the break-even hydrogen price until ca. 55% capacity. If the hydrogen production is used at half of its capacity (50% capacity factor), the break-even hydrogen price increases by 16.4 NOK/kg for Case A, and 16.6 NOK/kg for Case B. This shows that both cases are relatively flexible in terms of output, and that a potentially reduced demand in the first few years of the project would have only a moderate impact on the break-even production price and on the project profitability.

The actual hydrogen sales price, however, directly impacts the profitability of the project expressed in Net Present Value (NPV). Since Case B has twice the production capacity of Case A, its NPV is more sensitive to variations in hydrogen sales price than Case A. This means that for every increase in the hydrogen sales price, the profitability of Case B increases more than for Case A, as illustrated below.

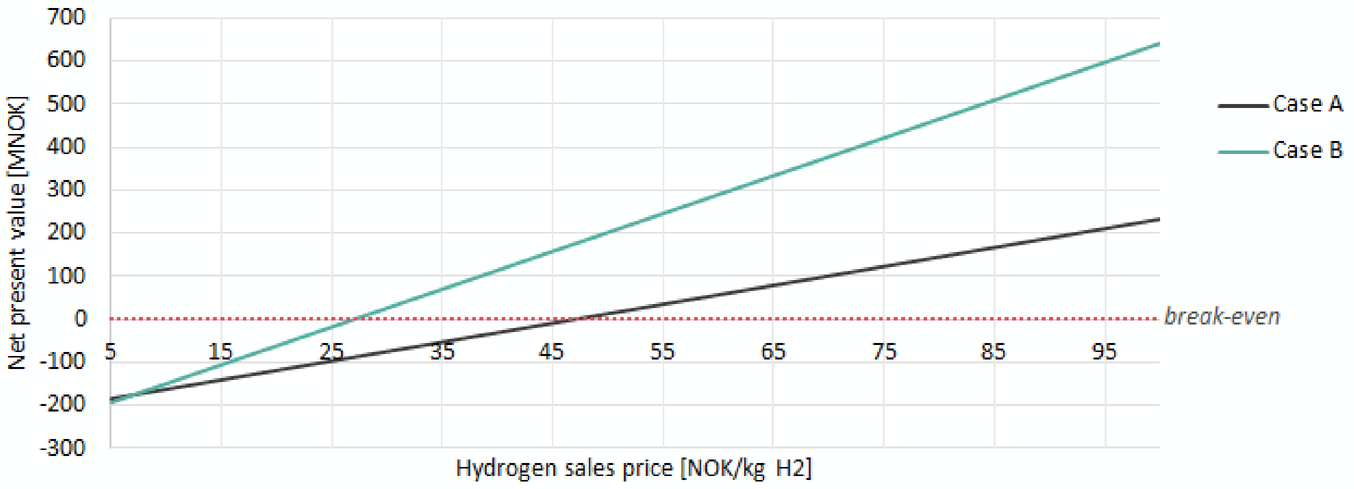


Figure 57 - Effect of the hydrogen sales price on the net present value for Case A and B

Note that the break-even price for Case A and Case B is set when the curves cross the X-axis on the figure above (dotted line in red color).

The discount rate used in the calculations influences the NPV of the project, and therefore influences the break-even production price for hydrogen. A discount rate of 7% was used as a base case, and the effect on the break-even price is illustrated in the figure below.

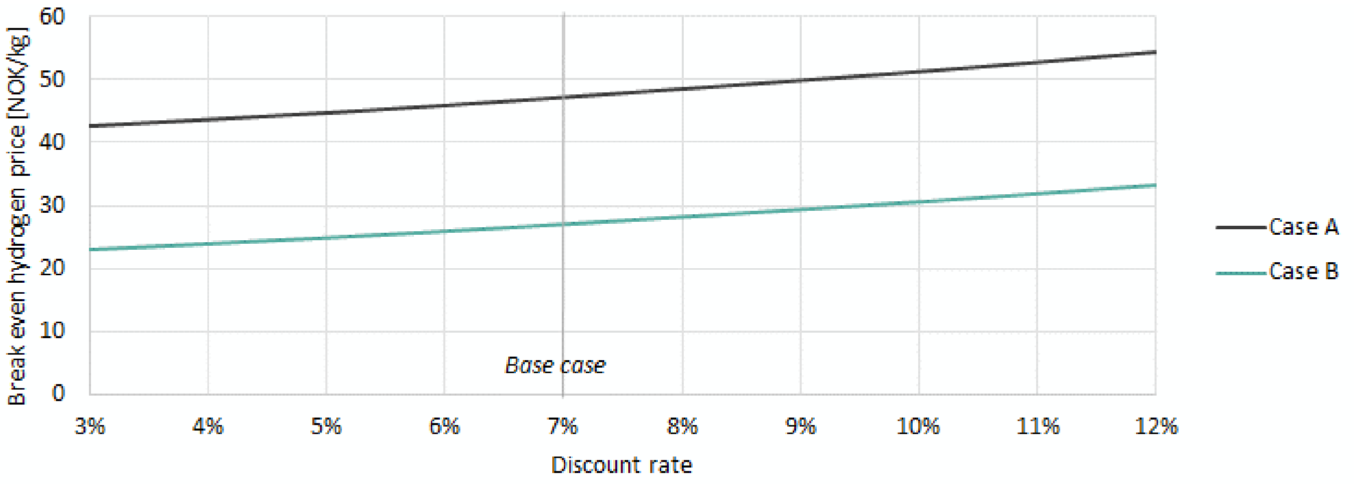
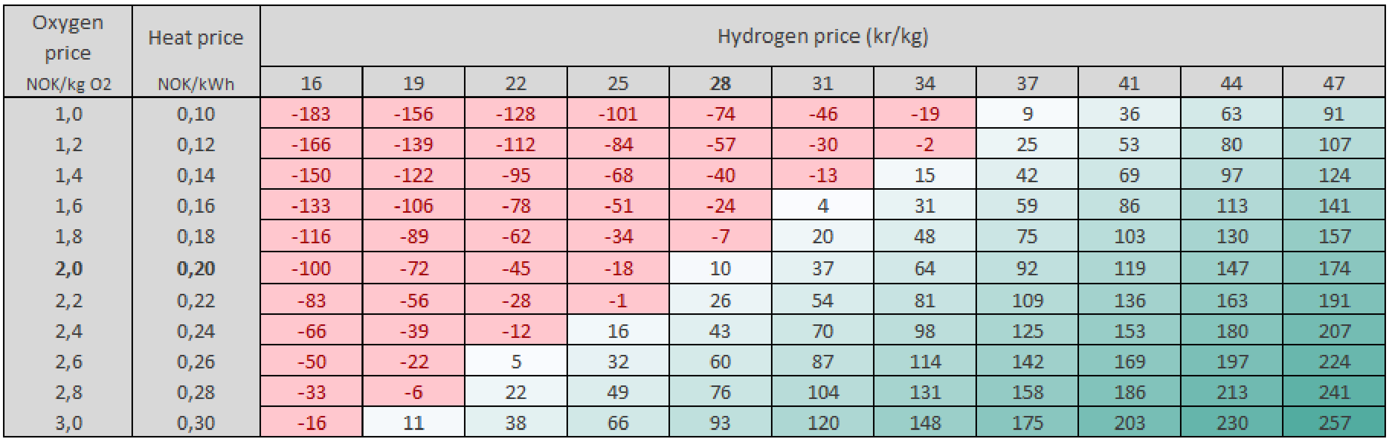


Figure 58 - Effect of the discount rate on the break-even hydrogen price for Case A and B

C3.3 INVESTMENT DECISION

The profitability of Case A and Case B is partly dependent on the hydrogen sales price, and on the potential oxygen and heat sales prices.

The figure below shows the Net Present Value (NPV, in MNOK) of Case B as a function of variations in hydrogen price (from 16 to 47 NOK/kg), in oxygen price (1.0 to 3.0 NOK/kg) and in heat price (0.1 to 0.3 NOK/kWh). Note that for simplification purposes the oxygen and heat prices are correlated in the figure. In practice these prices would be independent.

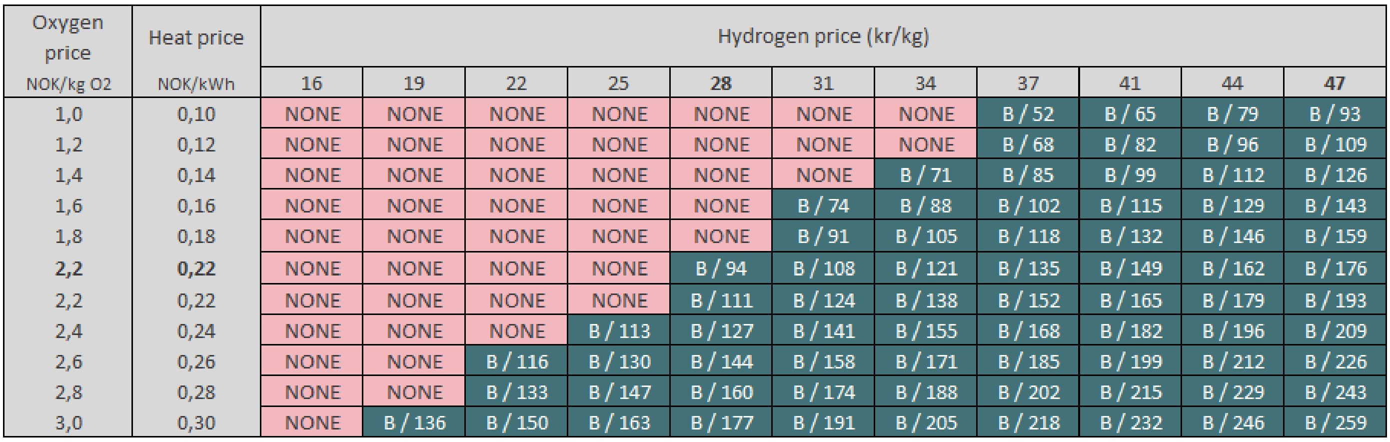


Oxygen price	Heat price	Hydrogen price (kr/kg)										
NOK/kg O2	NOK/kWh	16	19	22	25	**28**	31	34	37	41	44	47
1,0	0,10	-183	-156	-128	-101	-74	-46	-19	9	36	63	91
1,2	0,12	-166	-139	-112	-84	-57	-30	-2	25	53	80	107
1,4	0,14	-150	-122	-95	-68	-40	-13	15	42	69	97	124
1,6	0,16	-133	-106	-78	-51	-24	4	31	59	86	113	141
1,8	0,18	-116	-89	-62	-34	-7	20	48	75	103	130	157
2,0	**0,20**	-100	-72	-45	-18	10	37	64	92	119	147	174
2,2	0,22	-83	-56	-28	-1	26	54	81	109	136	163	191
2,4	0,24	-66	-39	-12	16	43	70	98	125	153	180	207
2,6	0,26	-50	-22	5	32	60	87	114	142	169	197	224
2,8	0,28	-33	-6	22	49	76	104	131	158	186	213	241
3,0	0,30	-16	11	38	66	93	120	148	175	203	230	257

Figure 59 – NPV of Case B as a function of hydrogen, oxygen and heat prices (MNOK)

The figure shows that for an oxygen price at 1.0 NOK/kg, and heat price at 0.1 NOK/kWh, hydrogen needs to be sold at least at 37 NOK/kg for the project to have a positive NPV, in other words to be profitable. An increase in both oxygen and heat prices allow for lower hydrogen production costs while still reaching a positive NPV, with as low as ca. 19 NOK/kg if all the oxygen and heat are sold at 3.0 NOK/kg and 0.3 NOK/kWh, respectively.

The figure below shows which of the cases A or B is the most profitable, and by how much the most profitable case increases the NPV (in MNOK), for each variation in hydrogen, oxygen and heat prices.



Oxygen price	Heat price	Hydrogen price (kr/kg)										
NOK/kg O2	NOK/kWh	16	19	22	25	**28**	31	34	37	41	44	**47**
1,0	0,10	NONE	NONE	NONE	NONE	NONE	NONE	NONE	B / 52	B / 65	B / 79	B / 93
1,2	0,12	NONE	NONE	NONE	NONE	NONE	NONE	NONE	B / 68	B / 82	B / 96	B / 109
1,4	0,14	NONE	NONE	NONE	NONE	NONE	NONE	B / 71	B / 85	B / 99	B / 112	B / 126
1,6	0,16	NONE	NONE	NONE	NONE	NONE	B / 74	B / 88	B / 102	B / 115	B / 129	B / 143
1,8	0,18	NONE	NONE	NONE	NONE	NONE	B / 91	B / 105	B / 118	B / 132	B / 146	B / 159
2,2	**0,22**	NONE	NONE	NONE	NONE	B / 94	B / 108	B / 121	B / 135	B / 149	B / 162	B / 176
2,2	0,22	NONE	NONE	NONE	NONE	B / 111	B / 124	B / 138	B / 152	B / 165	B / 179	B / 193
2,4	0,24	NONE	NONE	NONE	B / 113	B / 127	B / 141	B / 155	B / 168	B / 182	B / 196	B / 209
2,6	0,26	NONE	NONE	B / 116	B / 130	B / 144	B / 158	B / 171	B / 185	B / 199	B / 212	B / 226
2,8	0,28	NONE	NONE	B / 133	B / 147	B / 160	B / 174	B / 188	B / 202	B / 215	B / 229	B / 243
3,0	0,30	NONE	B / 136	B / 150	B / 163	B / 177	B / 191	B / 205	B / 218	B / 232	B / 246	B / 259

Figure 60 - Optimal investment decision as a function of hydrogen, oxygen and heat prices

The figure shows that Case B is the best investment decision for most combinations of hydrogen, oxygen and heat sales prices, when the prices are above a certain level (1.0 NOK/kg for oxygen and 0.1 NOK/kWh for heat). Case A is not the optimal investment decision for any of the cases above, due to the fact that its break-even hydrogen production price is much higher than with Case B. This is consistent with the results in Figure 57. Below a given hydrogen, oxygen and heat price, none of the cases are attractive (red color on the figure).

C3.4 INVESTMENT SUPPORT

The Smøla project would be well suited for the Norwegian Pilot-E program, which supports projects bringing together complete value-chain for hydrogen (Enova, 2019). The program has a total budget of 120 million NOK for 2019, funded by the Norwegian Research Council and Innovation Norway. The support is to be provided as a share of the project investment costs, and the degree of support was not yet confirmed at the time of this writing. The figure below illustrates the effect of a potential Pilot-E support to the Smøla project, assuming support up to 40% of the investment costs, for cases A and B.

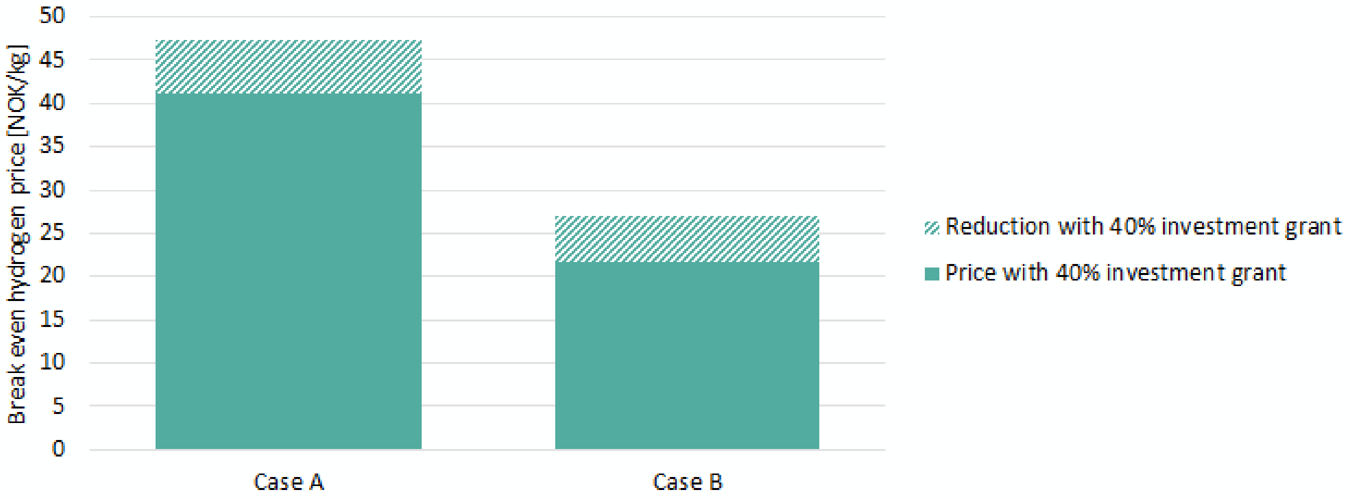


Figure 61 - Effect of the Pilot-E support on the break-even hydrogen price for Case A and B

Provided a 40% support on the investment costs, the break-even hydrogen production price could be reduced by 6.1 NOK/kg for Case A, and 5.4 NOK/kg for Case B. This represents a reduction of 12.9% and 20.0%, respectively. This moderate reduction is explained by the fact that support is provided for investment costs only, and that hydrogen production from electrolysis has high operational costs linked to energy use. Nevertheless, a large support to the investment costs could facilitate the project financing and its realization.

C3.5 BENCHMARKS - HOW HYDROGEN AT SMØLA COMPARE WITH OTHER PROJECTS

Figure 62 shows a comparison of the production cost at Smøla with the current retail price for hydrogen in Norway (ex. VAT) and for an equivalent in diesel, taking into account energy content and typical efficiencies for hydrogen fuel cells and diesel engines.

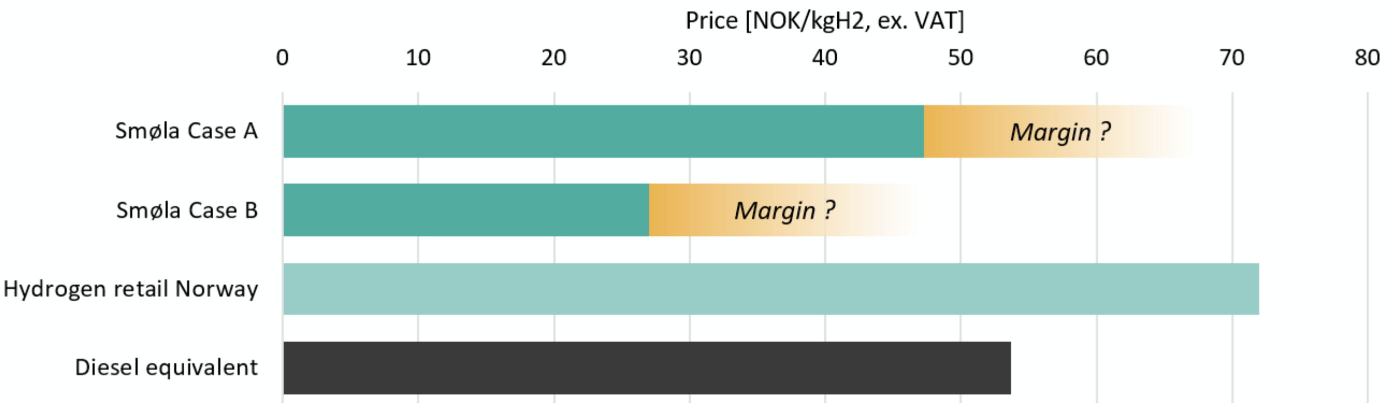


Figure 62 - Hydrogen production cost at Smøla, retail hydrogen price in Norway and diesel equivalent (pump price for private vehicles, ex. VAT)

In practice, the retail price for hydrogen from Smøla would be higher than the production costs. This is reflected on the figure above with a placeholder for a margin. The actual margin is undecided at the moment and would most likely vary depending on the type of customers, their willingness to pay, and the volumes procured. The transport sector, for example, is typically willing to pay more for fuels than the maritime or industry sectors.

Nevertheless, the figure shows that the hydrogen production costs at Smøla would be competitive against current hydrogen retail prices in Norway, even including a margin. When compared with diesel equivalent (pump price for private vehicles, ex. VAT), Case B is the one allowing for the largest margin while still being competitive in price.

The company in charge of hydrogen sales would be the one setting the hydrogen price for the different markets. This is typically subject to negotiations, on a case-by-case basis and depending on the customer’s sector, the volumes procured (lower prices for larger volumes), and the duration of the contract (lower prices for longer contracts). The ownership structure for production and sale of hydrogen from Smøla is not defined at this stage and is not within the scope of this assessment. NVES (2018) recommends establishing a development company, co-owned by public and private actors.

A comparison with other hydrogen projects from hydropower in Norway shows a strong correlation between the production capacity of the projects and the cost of production for hydrogen, as illustrated in Figure 63. Both Smøla case A and case B are close to the trend line for Norwegian projects. It should be noted that the projects include differing assumptions in terms of electricity costs, public support, sale of heat and oxygen, etc., which can explain the variations around the trend line.

The following studies are included in the comparison:

- Hellesylt Hydrogen Hub (Stranda kommune, 2017),
- Rotnes Bruk (NVE / IFE, 2017),
- Kvinnherad (Greensight, 2018a),
- Rullestad (SINTEF, 2018),
- Gloppen (Greensight, 2018b).

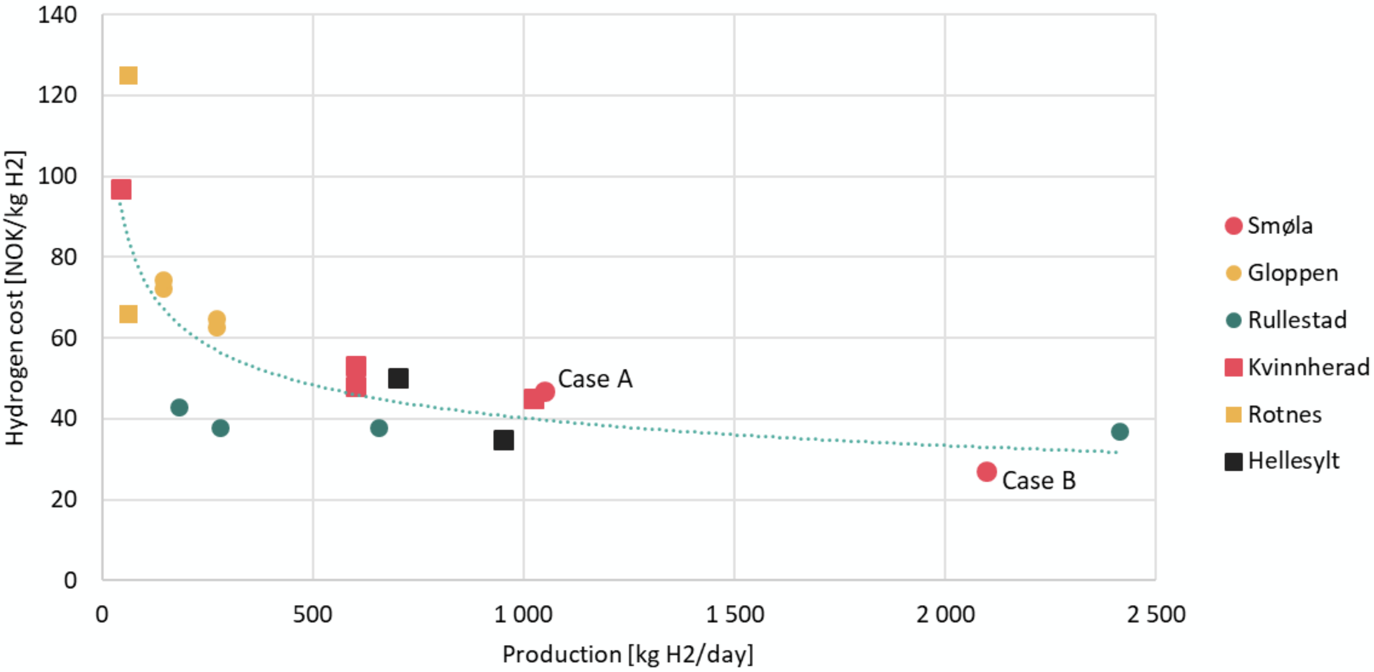


Figure 63 - Correlation between hydrogen production and hydrogen cost

In terms of footprint, both case A and case B are close to the median on benchmarks provided by NewBusFuel (2017). The footprint has not been optimized, since both site 1 (Edøy) and site 2 (Vikan) do not have area constraints.

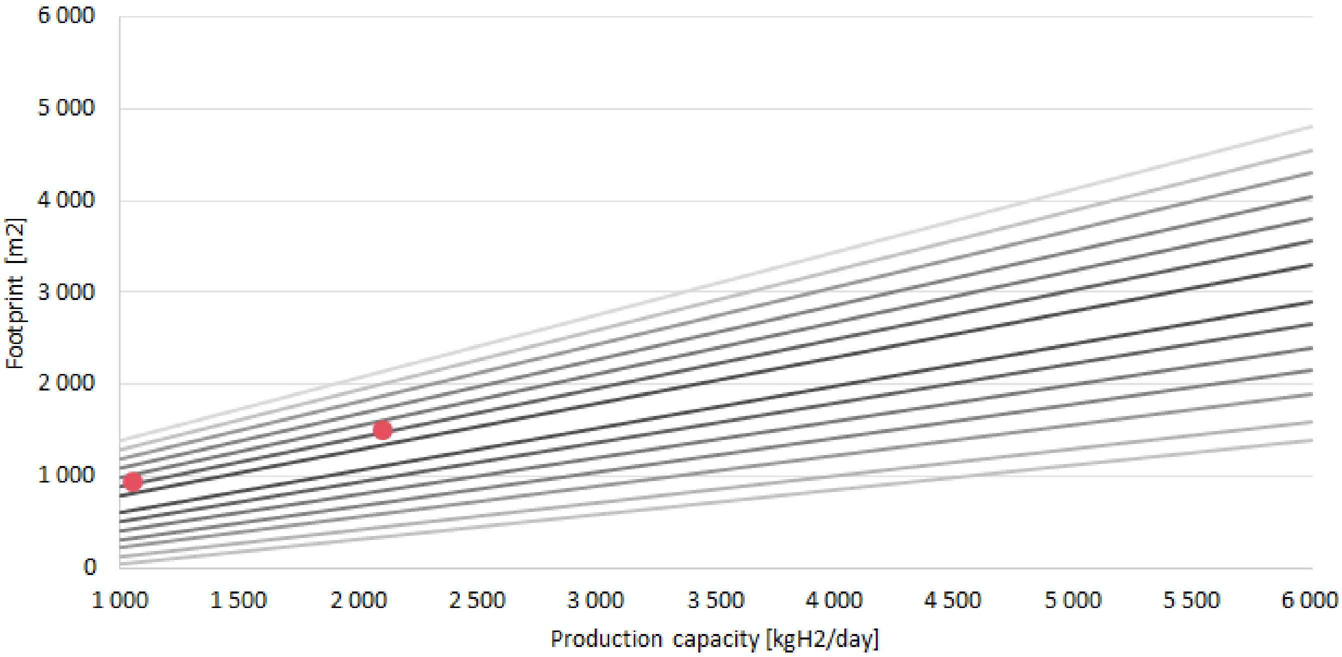


Figure 64 - Smøla production case A and case B compared to a benchmark for footprint use (m^2) for hydrogen refueling stations with on-site production. Source: Endrava, based on benchmark from NewBusFuel (2017)

NewBusFuel (2017) provides other interesting benchmarks for hydrogen production and distribution, in terms of CAPEX and OPEX for different production capacities and utilization factors. These benchmarks are not included in this report due to differences in scope that make comparison with the Smøla project difficult.

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APPENDIX D - ENVIRONMENTAL EVALUATION

D1 WELL TO WHEEL EMISSIONS OF DIESEL AND HYDROGEN

D1.1 HYDROGEN CARBON FOOTPRINT

When used in fuel cells, hydrogen emits only water, and is therefore considered zero-emissions. Indirectly, there are however greenhouse gas emissions linked to the production of hydrogen, depending on its origin. In the case of Smøla, the indirect GHG emissions are expected to be very low, since the hydrogen would be produced from wind energy.

From a life-cycle perspective, the following activities lead to indirect GHG emissions for hydrogen production and distribution at Smøla:

- equipment: production of the electrolyzer and other hydrogen-related equipment, its installation, maintenance and future decommissioning,
- wind energy used: a share of the production, installation, operation, maintenance and future decommissioning of the wind park,
- transport: fuel and equipment used for transport of the hydrogen from the production site to the users,
- distribution: production of the local equipment and dispensers, their installation, operation, maintenance and future decommissioning.

A full LCA analysis would be needed in order to be able to precisely estimate the GHG footprint of the hydrogen production at Smøla. Since this is not part of the scope of this project, relevant research publications are used as a basis for the assessment.

D1.1a Hydrogen production

Valente et al. (2017) developed a method for harmonizing carbon footprint results from LCA of hydrogen energy systems, and applied it to 71 case studies. The article includes a comparison of the results from 11 case studies relevant to Smøla on water electrolysis from wind power. The results are harmonized with a functional unit of 1 kg hydrogen at a pressure of 200 bars. The harmonization of pressures is important, since compression is energy-intensive. The 11 case studies indicate carbon footprints varying from 0.51 kg_{CO2e}/kg_{H2} to 2.02 kg_{CO2e}/kg_{H2}, with an average value at 1.02 kg_{CO2e}/kg_{H2}. These values include the indirect carbon footprint from the wind energy used, and the production and use of machinery, equipment and buildings for hydrogen production. The hydrogen pressure at Smøla is 350 bar, and Endrava estimated the additional carbon footprint linked to compression (from 200 to 350 bar) to be 0.0035 kg_{CO2e}/kg_{H2}. Hydrogen production at Smøla could therefore have a carbon footprint of 1.03 kg_{CO2e}/kg_{H2}, or 8.6 gCO2/MJ when expressed in energy content.

Spath et al. (2004) calculated that the wind turbines production and operation accounts for 78% of the carbon footprint of hydrogen from wind power, due to the steel and concrete requirements. In comparison, the study shows that only 4.4% of the footprint is linked to the electrolysis production and operation. According to the study, the carbon footprint of the electrolyzer is therefore very limited compared to the source of the electricity itself. In the case of Smøla, the hydrogen would be produced from excess electricity that cannot be exported to the users due to the limitations in the sea cable to shore. One could therefore argue that the carbon footprint of the energy used is marginal and that hydrogen from Smøla should not be attributed the full carbon footprint of the electricity from wind. The rest of this assessment will however be based on the full carbon footprint and may therefore be considered as conservative.

D1.1b Hydrogen transport and distribution

Little data is available on the carbon footprint of the hydrogen transport and distribution to the consumers. Endrava estimated the additional footprint linked to truck transport to be 0.320 kg_{CO2e}/kg_{H2} (2.67 g_{CO2}/MJ) for transport to a consumer located at 100 km distance with a conventional diesel truck (including return trip with empty tanks). The calculation does not include the production and maintenance of the transport equipment.

Simon and Bauer (2011) indicates ca. 1 kg_{CO2e}/kg_{H2} for 100 km transport. The difference is due to different assumptions, including much heavier transport tanks: 33 tonnes freight weight for 335 kg_{H2} in Simon and Bauer (95 $kg_{freight}/kg_{H2}$), and 19 tonnes for 885 kg_{H2} in the current study (21 $kg_{container}/kg_{H2}$). This difference in weight is due to much lighter composite cylinders from Hexagon assumed to be used in this study.

Transport and distribution is not further included in the assessment, but may have an effect if the hydrogen is transported to users located far away from the hydrogen production site. In practice, however, transport costs would most likely be the limitation to transport distance before the transport carbon footprint is too high, as illustrated in the figure below.

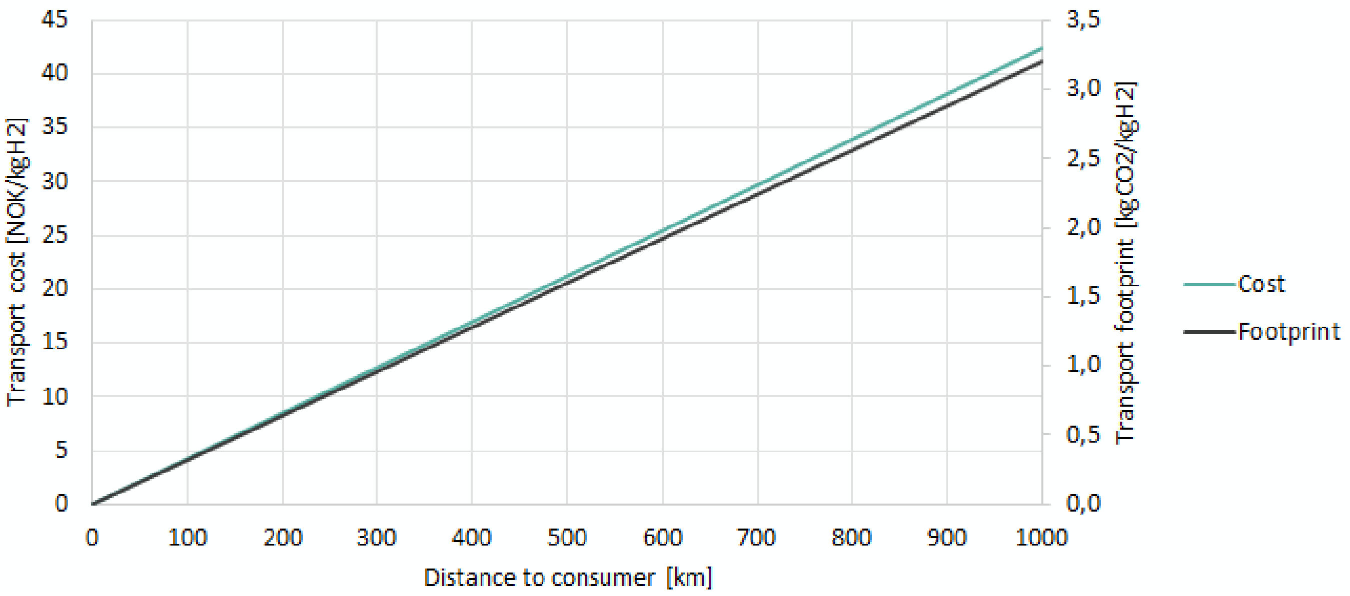

Figure 65 - Relation between distance to consumer, transport cost and transport footprint

The calculations are based on transport costs as provided by TØI (2018), with an assumed 60 km/h average speed, and taking into account the distance to bring back the empty containers to Smøla.

D1.1c Hydrogen from natural gas as an alternative

As a basis for comparison, Steam Methane Reforming is the most common method for producing hydrogen in the world, from natural gas, with 49% of the production (IHS Markit, 2018). Valente et al. (2017) indicates a carbon footprint of 12.95 kg_{CO2e}/kg_{H2} for SMR without CCS. Mehmeti (2018) indicates a range between 8.9 and 12.9 kg_{CO2e}/kg_{H2} from various studies. The production of hydrogen from wind power at Smøla would therefore have a carbon footprint 13 times lower than that of Steam Methane Reforming with natural gas.

In the case of SMR with CCS, data from Mehmeti (2018) and Dufour et al. (2009) indicate carbon footprint of 3.07 kg_{CO2e}/kg_{H2} and 3.28 kg_{CO2e}/kg_{H2}, respectively.

The figure below summarizes the carbon footprint of these hydrogen production technologies.

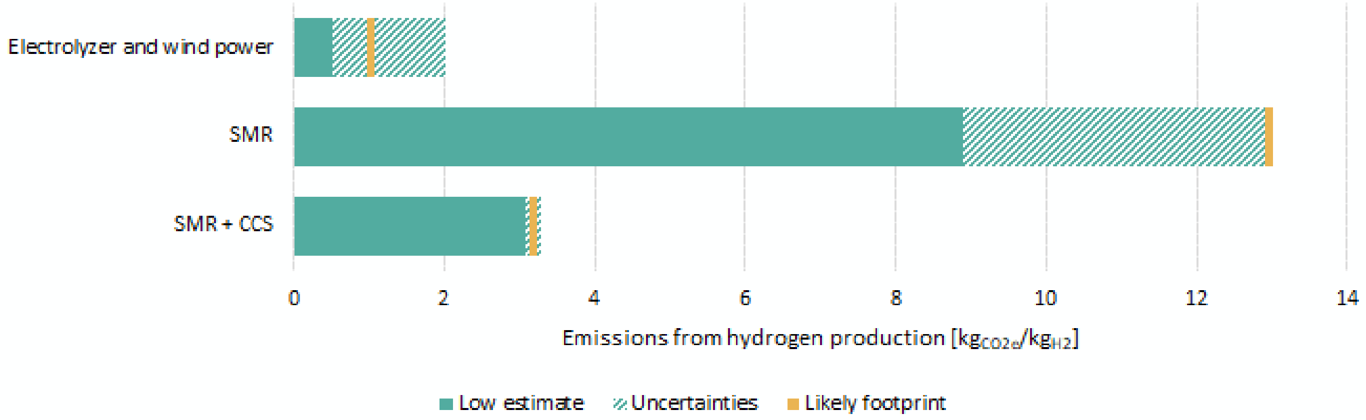

Figure 66 - Carbon footprint of hydrogen from wind energy and from SMR, without and with CCS

D1.2 DIESEL CARBON FOOTPRINT

Keesom et al. (2012) indicates a carbon footprint of 91.5 g_{CO2}/MJ for diesel in Europe. This includes 16.5 g_{CO2}/MJ for the production, refining and transport of diesel (well to tank), and 75 g_{CO2}/MJ for the diesel combustion in engines (tank to wheel). This is equivalent to a total carbon footprint of 3.28 kg_{CO2e}/l_{diesel}.

The diesel carbon footprint is therefore 10.6 times higher than that of hydrogen from wind power calculated above, based on the respective energy content of the fuels (LHV).

D1.3 GHG EMISSION REDUCTIONS PER LITER DIESEL EQUIVALENT

For comparing hydrogen and diesel emissions on more precise basis, the energy efficiency of the power trains has to be included in the assessment. Assuming an efficiency of 40% for hydrogen fuel cells and electric motors (NVES, 2017), and 30% for the diesel engine, one liter of diesel used in a conventional engine is equivalent to 0.224 kg hydrogen in a fuel cell with electric motor.

This theoretical value is close to what is reported for vehicles:

- 0.20 kg_{H2}/l_{diesel} for buses, assuming 10 kg_{H2}/100km and 50 l_{diesel}/100km.
- 0.21 kg_{H2}/l_{diesel} for cars, assuming 0.95 kg_{H2}/100km and 4.5 l_{diesel}/100km.
- 0,182 kg_{H2}/l_{diesel} for a potential live fish carrier boat, assuming 273 $tonnes_{H2}$/year, and 1,500 m^3_{diesel}/year

Based on the carbon footprints for diesel and hydrogen calculated above, this means that for every liter of diesel replaced with hydrogen from Smøla in a vehicle, ca. 3.05 kg_{CO2e} would be saved, as illustrated below. Note that this is a generic value, and there may be variations depending on the type of vehicle.

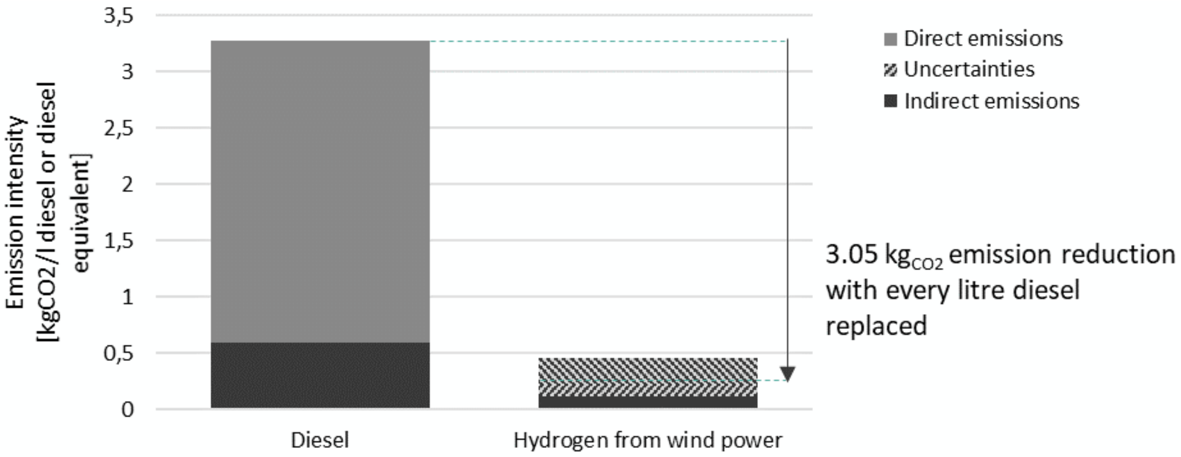

Figure 67 - GHG emission savings with the use of hydrogen instead of diesel in vehicles

Converted in terms of hydrogen, 13.6 kg_{CO2e} would be saved per kilogram hydrogen used, when replacing diesel.

D2 GHG EMISSION REDUCTIONS FROM HYDROGEN USERS

Based on the hydrogen demand scenarios calculated in appendix B, and on the reduction factors calculated in the previous section, it is possible to calculate the potential GHG emission reductions from hydrogen users at Smøla and in the county.

The figure below summarizes the potential emission reductions from the use of hydrogen at Smøla.

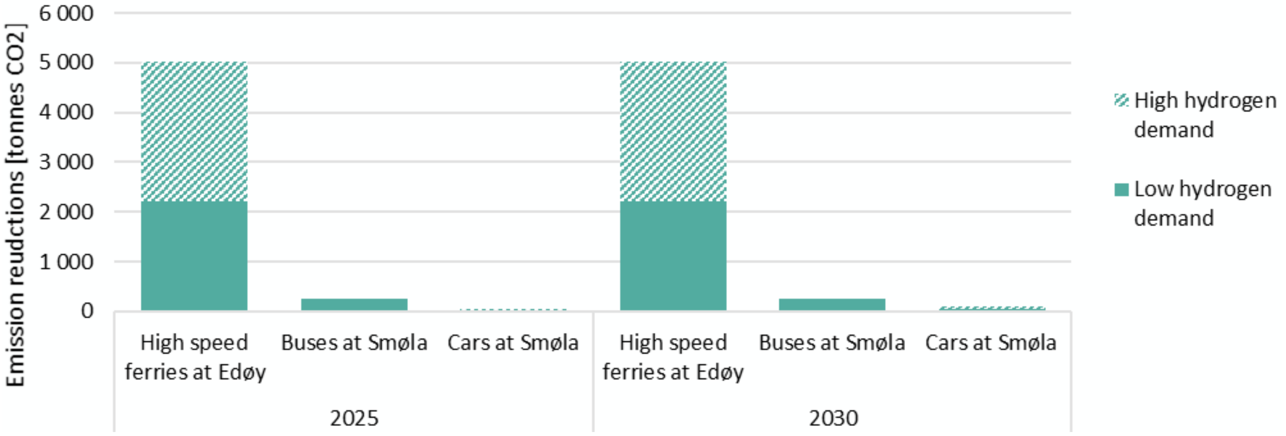

Figure 68 - Emission reductions with hydrogen users at Smøla, 2025 and 2030

By 2025, emission reductions of ca. 5,306 $tonnes_{CO2e}$ could be achieved at Smøla by implementing hydrogen on the high speed ferries, and by fueling buses and cars. This potential corresponds to a high case demand for hydrogen (see also appendix B). In case of low demand, the reductions could amount to 2,500 $tonnes_{CO2e}$. It should be noted that hydrogen dispensers for cars are different than for buses (typically 700 bar vs. 350 bar), and that the implementation of a hydrogen dispenser for cars was not included in the project assessment.

By 2030, the emission reductions from users at Smøla could increase to 2,526 $tonnes_{CO2e}$ (low case) and 5,358 $tonnes_{CO2e}$ (high case). Of these reductions, 88% would be direct emissions (tank to wheel), and 12% would be indirect (well to tank).

Based on the hydrogen production in Case A and Case B (appendix C), with a production capacity of 1.05 $tonnes_{H2}$/day and 2.1 $tonnes_{H2}$/day, respectively, the emission reductions from production of hydrogen at Smøla would be 5,171 $tonnes_{CO2e}$/year for Case A, and 10,342 $tonnes_{CO2e}$/year for Case B. This is based on the assumption that all the hydrogen produced at Smøla would replace the use of diesel.

D3 OTHER ENVIRONMENTAL EFFECTS

Simon and Bauer (2011) provide a comparison of emissions from well to wheel for diesel and a range of hydrogen production processes, on an energy content basis. According to the authors, hydrogen from wind has about ten times lower non-methane VOC (NMVOC) emissions than diesel, and seven times lower NOx emissions. SO_X emissions are about the same between both fuels from a well to wheel perspective. Production and use of hydrogen from wind energy produces about twice as much particulate matter emissions (PM <10µm) than the use of diesel in a combustion engine. It should be noted that the engine used as a reference in the study is EURO 3, and that progress has been made on emission levels with newer engines, in particular for NOx emissions. While much of the emissions from diesel would happen locally, almost all emissions from hydrogen are linked to production and installation of the necessary equipment (wind turbines, electrolyzer, tanks, etc.).

A full life cycle analysis would be required in order to assess other environmental impact categories for the production of hydrogen from wind energy: water depletion, acidification, ecotoxicity, land use, etc.

In terms of noise, most of the hydrogen production equipment is silent, except for the compressors. In use, hydrogen fuel cell vehicles are much quieter than their diesel equivalents.

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Endrava is a consulting company based in Oslo, Norway. We support organizations and businesses in embracing sustainability opportunities.

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