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Abstract

The main aim of the ELEGANCY project is to accelerate the deployment of Carbon Capture and Sequestration (CCS) technologies in Europe through H_2-CCS chain networks. 5 country case studies are included as part of WP5.

This document provides an overview of H_2 utilisation numbers and CO_2 storage options for the Norwegian case study. A consistent set of H_2 utilisation numbers for transportation and industrial use is provided for different cases that will be utilized for scenario development of the Norwegian case study. H_2 ustilisation in the Nowegian transport sector and industrial sector are presented. While the transportation sector can potentially have a demand of 35 000 – 60 000 t of hydrogen per annum, the potential utilization in the industrial section is an order of magnitude higher. The main sources of industrial utilization considered are using H_2 as fuel for meeting heating requirements and steam generation in industries, offshore gas turbines and using H_2 as reduing agent, in addition to already existing applications such as ammonia and methanol production. The H_2 utilisation in the industrial section is around 300 000 – 400 000 t of hydrogen per annum.

A short overview of CO_2 storage in the Norwegian continental shelf is also given. Further, to provide a sense of perspective, a link between the H_2 utilisation numbers and corresponding CO_2 emissions capture for storage are compared with the CO_2 storage options being developed as part of the Northern Lights project and the full-scale Norwegian CCS project.

TABLE OF CONTENTS

Page

1 INTRODUCTION

The main aim of the ELEGANCY project is to accelerate the deployment of Carbon Capture and Sequestration (CCS) technologies in Europe through H_2-CCS chain networks. 5 country case studies are included as part of WP5. This document provides an overview of H_2 utilisation numbers and CO_2 storage options for the Norwegian case study. The preliminary aim of this work is to provide a consistent set of H_2 utilisation numbers for different cases that will be utilized for scenario development of the Norwegian case study.

CO_2 storage options in Norway have been extensively studied both by government and private actors. Thus, based on feedback from industrial partners, there is less focus in this document on CO_2 storage.

2 POTENTIAL H_2 UTILISATION IN THE TRANSPORT SECTOR

As a starting point, the Norwegian national transportation plan[1] sets the following target numbers for zero-emission transport agents in 2030, presented in Table 2.1.

Table 2.1 - Estimated numbers of zero-emission transport agents in 2030.

Busses	8 500
Light transport (< 3.5 t)	Some percentage of the total fleet
Heavy transport (> 3.5 t)	7 500
Ferries	Some percentage of the total fleet

It should be noted that similar incentives as for today's battery-driven cars (free parking, free toll roads, etc) are scheduled for hydrogen cars until 2025 or a number of 50 000 vehicles has been registered. Further, a total of 40% of close-proximity shipping (i.e. ships that operate in areas subject to Norwegian law) are supposed to be emission free by 2030. As most of the train network is electrified already, there is no special category in the list above. The first H_2 fuelled passenger trains have been pushed into service recently[2] and there are plans to fuel the 'Raumabanen' by hydrogen, estimated to consume about 164 tons/year H_2.[3]

It is of great importance to project consumptions of individual transport agents. DNV GL[4] suggest employing de-facto annually driven kilometers, readily attainable from the 'Statistisk Sentralbyrå' webpage[5] and convert to annual consumption by technical consumption rates per kilometer.[6] As technology is presently developing, there is variation in reported hydrogen consumption per km. the DNV GL report[4] cites a phone conversation with ASKO personnel, estimating characteristic hydrogen consumption for lorries of 0.17 kg/km, contradicted by other references[6] that refer to 0.08 kg/km for a similar project in Switzerland. Similarly, the FCH project (Fuel Cells and Hydrogen – Joint Undertaking) documents varying consumption rates throughout Europe (0.08 kg/km Aarau, CH; 0.013 kg/km Oslo; 0.22 kg/km Berlin, DE).[7] Performing an average over all performances yields 0.1 kg/km. For private cars, taxis and light transport vehicles the consumption rate is 0.01 kg/km.[6]

The annual consumptions for hydrogen-fueled transport agents of interest shown in Table 2.2.[4]

Table 2.2: Individual annual consumption rates.

Bus	3 900 kg
Light transport	123 kg
Taxi	580 kg
Heavy transport	8 640 kg
Raumabanen	164 000 kg
Small/medium sized ferry	180 000 – 365 000 kg
Large ferry	up to 2 600 000 kg

The most challenging part in this projection exercise is clearly to 'speculate' the number of total consumers, in particular, the total annual H_2 consumption by the transport sector in Norway will be dominated by the estimate on hydrogen-driven ferries. Particular care should be taken to evaluate consequences of large-scale road projects such as 'Ferjefri E39',[8] rendering at least 17

[1] Nasjonal Transportplan 2018-2029: Grunnlagsdokument
[2] Alstom - https://www.alstom.com/press-releases-news/2018/9/world-premiere-alstoms-hydrogen-trains-enter-passenger-service-lower
[3] Tomasgard et al., Nasjonale rammebetingelser og potensial for hydrogensatsingen i Norge. 2016
[4] DNV GL - Rapportnr. 2016-0931, Rev.1 - www.dnvgl.com
[5] Statistisk Sentralbyrå - www.ssb.no
[6] Hydrogenforum - www.hydrogen.no
[7] Fuel Cell Electric Buses - www.fuelcellbuses.eu/category/performance-data-0
[8] Ferjefri E39 - www.vegvesen.no/vegprosjekter/ferjefriE39

ferries obsolete. In addition, the number of operational ferry connections is highly variable. Today there are 140 operational ferry connections in Norway,[9] a total of 430 operational ferries seems a good approximation.[10] 'Statens vegvesen', the Norwegian national transport authority, refers to 120 operational connections and 200 ferries.[11] Generally, Statens vegvesen has a vision of powering 2/3 of all ferries by batteries, with the option of fueling the remaining ferries by biodiesel, biogas or hydrogen. This effectively caps the hydrogen-driven ferries at 33%. As the first operational hydrogen ferry is to be operational by 2021, the number of hydrogen-driven ferries will likely be small in 2030 and possibly larger thereafter. Tomasgard et al.[3] operate with 4-25 ferries in their analysis. Setting the percentage of hydrogen-fueled ferries to 10% in this work, then results in 20-40 ferries. This effectively suggests equal in-phasing of biogas, biodiesel and hydrogen. A typical small/medium car ferry is assumed to consume about 1 ton hydrogen a day, whereas large ferries may consume up to 7 tons per day.[4,10]

The numbers obtained from the National Transport Plan (NTP) for zero-emission transport[1] could be weighted similarly as for the ferries, i.e. setting the in-phasing of hydrogen-fuel throughout the transport sector to 10% of all available zero-emission technologies, ascribing hydrogen technology the same 'impact' as biodiesel and biogas.

2.1 Equal-share scenario

As described above, a first estimate is obtained by assuming that zero-emission technology is comprised of 2/3 electric battery drive and approximately 20% biogas and biodiesel. The numbers from the NTP are then weighted by 10% to produce the specific hydrogen consumptions listed in Table 2.3.

Table 2.3. Hydrogen consumption per transport agent.

Agent	Fleet [%]	Total fleet	Total consumption [t]
Bus	10	8 500	2 769
Heavy transport	10	7 500	2 655
Light transport	2	496 000	1 429
Private car	2	2 418 000	5 991
Taxi	30	8 200	1 434
ferry	10	200	7 300

The percentage of taxis is set to 30% as it is expected that this branch has higher potential to utilize new technologies, as has been the case for the introduction of electric-battery drive. The estimate is taken Tomasgard et al.,[3] whence the number of taxis is assumed to stay at similar level as today. The total amount of 'light' vehicles (< 3.5 t) is assumed to remain constant, as is the relative percentage among private cars and light transport vehicles. 2% of the total light vehicle fleet amounts to approximately 62 000 fuel electric cell vehicles (FECV). This number corresponds to a medium-low scenario, compared to Tomasgard et al.[12] Consumption rates for road transport are based on hydrogen consumption per driven kilometer and average annual driving lengths are taken from Statistics Norway,[5] and are assumed to remain at the same level as today. For the total number of ferries, the lower value (Statens vegvesen) is employed. The net annual consumption from the table sums to 21 581 t hydrogen. Also considering a 10% hydrogen share on the 40% zero-emission goal for close-proximity shipping produces additional 14 000 t hydrogen (based on 2013 rates of 1 079 374 t diesel equivalence emission in Norwegian ports[4]). Annual hydrogen consumption from the transport sector in this scenario reads **35 581 t per year**.

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[9] Ferjedatabanken - www.fdb.triona.no
[10] DNV GL - Rapportnr. 2015-0500, Rev. 0 - www.dnvgl.com
[11] Statens Vegvesen - www.vegvesen.no
[12] See footnote 3

2.2 Scaled DNV-GL scenario

A utilisation study for Western-Norway has been performed by DNV-GL.[5] Here the corresponding numbers for the whole of Norway are presented scale from the report. For the hydrogen-fueled taxi fleet percentage, the medium scenario in Tomasgard et al.[3] is taken, i.e. 30% hydrogen powered taxis. Hydrogen-drive of the Raumabanen is also considered. Numbers for FCEV below 3.5 t are capped at 50 000 (1% of the total fleet today). Potential hydrogenisation of the heavy transport is assigned a higher share of 25% compared to the previous section, as is the hydrogen ferry share of 20%. Corresponding annual consumption rates are listed in Table 2.4.

Table 2.4: Hydrogen consumption per transport agent.

Agent	Fleet [%]	Total fleet	Total consumption [t]
Bus	10	8 500	2 769
Heavy transport	25	7 500	6 638
Light transport	1.6	496 000	1 143
Private car	1.6	2 418 000	4 793
Taxi	30	8 200	1 434
Raumabanen	100	1	164
ferry	20	200	14 600

The total hydrogen consumption in this scenario sums to approximately 31 543 t. The DNV-GL report[5] also suggests 20% hydrogen share on close-proximity shipping emissions, adding 28 000 t for a total of ca **59 543 t per year**.

2.3 Comment

The uncertainty involved in the presented estimate is considerable. Information on consumption per km for hydrogen-fueled heavy transport and buses is subject to great variance as technology is still in the development/testing phase. It should also be noted that contracts for many ferry connections are assigned for long time periods (typically 10 years), such that in-phasing of hydrogen ferries could occur later than assumed here. Further, the presented estimate is very sensitive to the number of operational hydrogen ferries. DNV-GL[10] have suggested that electrification of 52 ferry connections (with a total of 63 unique ferries) is feasible. From this point of view and the same level of hydrogen implication, the estimate of annual consumption would drop by 25% in the equal-share scenario (I) and 33% in the scaled DNV-GL scenario (II).
Assuming that hydrogen technology will not be routinely implemented on ferries or close-proximity shipping before 2030, knowledge of hydrogen consumption per driven km is vital. Some manufacturers operate with rates as low as 0.05 kg / km for buses and heavy transport. The total consumption then reduces on the order of 20% in both cases. Allowing higher consumptions of up to 0.2 kg / km, net consumption increases by 40% and 60% respectively in scenarios I and II.

Tomasgard et al.[3] have studied in-phasing and economic feasibility of hydrogen technology into the transport sector. Estimates for lacking facilitation ('low') and optimistic expectations for technological development and implementation ('high') resulted in 9 000 t hydrogen per year for the low scenario and 61 000 t hydrogen per year for the high scenario. Significant deviations to the present estimate are associated with varying consumption rates for heavy transport and buses as well as for the assumed number of ferry connections fueled by hydrogen. Also, no consideration of hydrogenisation in close-proximity shipping has been executed there.

3 POTENTIAL H_2 UTILISATION IN THE INDUSTRIAL SECTOR

3.1 H_2 as fuel

Natural gas has been primarily used as a fuel in the Norwegian industry to provide heat and/steam. It is assumed that at some point in the future *all* energy supply stemming from natural gas to the industry may be covered by hydrogen. 33 kWh may be obtained from converting 1 kg of hydrogen. Statistisk Sentralbyrå gives the annual energy consumption rate for the industry sector in 2015 as 75 219 GWh.[13] 1 657 GWh has been acquired from natural gas (NG) in gaseous form (2.2% of total consumption) and 1 358 GWh from liquefied natural gas (1.8% of total consumption).[14] The corresponding hydrogen tonnage is presented in Table 3.5.

Table 3.5: Hydrogen equivalent energy consumption from NG.

Source	Consumption [GWh]	Hydrogen equivalent [t]
Gaseous NG	1 657	40 950
Liquefied NG	1 358	50 050

3.2 Ammonia production

When producing ammonia, approximately 5.6 t ammonia may be obtained from 1 t hydrogen. This follows from the reaction

$$3\,H_2 + N_2 \rightarrow 2\,NH_3.$$

Stoichiometrically 5.67 t ammonia is produced from 1 t hydrogen. Per today, ammonia is produced at Yaras Porsgrunn facility, where about 500 000 t ammonia are produced annually. This amounts to ca 88 000 t hydrogen feedstock.

3.3 Methanol production

Similarly, about 6.9 t methanol ca be produced from 1 t hydrogen.[15] Equinor's methanol facility at Tjeldbergodden produces about 900 000 t methanol per year, which corresponds to an annual consumption of 130 000 t hydrogen.

3.4 Tyssedal Titanium production

The TiZir Titanium ilmenite facility in Tyssedal is scheduled to substitute coal with hydrogen in the reduction process with an annual hydrogen consumption of 11 000 t.[16] Full scale operation is set to start in 2020.

3.5 Mongstad refinery

Equinor and Greenstat are investigating a possible hydrogen production site at the Mongstad refinery,[17] whose annual hydrogen consumption is estimated at 11 000 t.

3.6 Offshore gas turbines

In 2013 the Norwegian Petroleum Directorate published details on turbines employed for offshore oil and gas production.[18] The details stem from investigations performed in 2012. Without further information it is not possible to determine the exact amount of equivalent hydrogen consumption, as only turbine effects are provided as well as total operating hours. We assume average runtimes

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[13] Note that energy consumption is according to SSB: energy products employed for production, light, heat and transportation. Energy products employed as feedstock are precluded from this number.

[14] SSB - www.ssb.no/energi-og-industri/statistikker/indenergi - Tabell 5

[15] See footnote **Error! Bookmark not defined.**

[16] www.sysla.no/gronn/startskudd-for-storskala-hydrogenproduksjon/

[17] GREENSTAT - "Making Norway even greener" 2015

[18] www.npd.no/global/norsk/3-publikasjoner/rapporter/oversiktskjema-motorer-og-turbiner.xls

of 85% throughout the year. The lower heating value of 1 kg hydrogen corresponds to 33 kWh of energy or 120 MJ. A 1 MW electric effect (MWe) gas turbine operating at efficiency η needs to be fueled 1/η MW thermal effect. Consequently, the corresponding hydrogen consumption rate reads $(120\ \eta)^{-1}$ kg / s. Accordingly, a 34% efficiency 1 MWe gas turbine operational throughout the year produces comparable electric energy as may be obtained from 773 t hydrogen. Note that dual-, diesel- and gas turbines employed for torch operation are discarded, due to lack of information. Table 3.6 provides location of the oil/gas field, normal turbine capacity (electric effect), electric efficiency η and corresponding yearly hydrogen consumption, given that the turbines are operational throughout the year.

The summed estimated hydrogen consumption per year reads 781 463 t. Using an estimate of 85% operation, the consumption reduces to **664 244 t hydrogen per year**. Clearly, there lies a great potential for hydrogen utilisation in offshore gas turbine power supply. The average gas turbine from Table 3.6 has a total capacity of 22.14 MWe, operates at normal load 17.66 MWe, features electric efficiency of 34.84 % and may be compared to 13 245 t hydrogen consumption at 100 % operation throughout the year. 85% operational hours suggests the comparable amount of **11 258 t hydrogen in one year per gas turbine**.

Table 3.6: Offshore-gas-turbine specifications.

Location	Norm. capacity [MW]	Efficiency [%]	Consumption [t/yr]
Ekofisk 2/4 J	14	37	9 935
Ekofisk 2/4 J	14	37	9 935
Ekofisk 2/4 J	21	37	14 916
Ekofisk 2/4 J	21	37	14 916
Ekofisk 2/4 J	16	37	11 364
Ekofisk 2/4 J	16	37	11 364
Ekofisk 2/4 K	11	37	7 813
Ekofisk 2/4 K	11	37	7 813
Ekofisk 2/4 K	11	37	7 813
Ekofisk 2/4 K	3.1	28.5	2 859
Ekofisk 2/4 K	3.1	28.5	2 859
Ekofisk 2/4 K	3.1	28.5	2 859
Eldfisk 2/7 E	9.9	37	7 032
Eldfisk 2/7 E	9.9	37	7 032
Eldfisk 2/7 E	9	37	6 392
Eldfisk 2/7 E	9	37	6 392
Eldfisk 2/7 E	17	37	12 075
Gjøa	24.5	37.5	17 170
Grane	11	35	8 259
Grane	24	35	18 021
Gullfaks A	19	37	13 495
Gullfaks A	19	37	13 495
Gullfaks A	19	37	13 495
Gullfaks C	19	37	13 495
Gullfaks C	19	37	13 495
Heidrun TLP	28	32	22 995
Huldra	9	30	7 884
Njord A	18	36	13 140
Norne FPSO	19.23	35.7	14 156
Norne FPSO	19.23	35.7	14 156
Oseberg Sør	18	35	13 515
Oseberg Feltsenter	23.5	36.5	16 920
Oseberg Feltsenter	23.5	36.5	16 920

Skarv FPSO	30.8	37.5	21 585
Sleipner A	21.3	33.3	16 810
Sleipner A	21.3	33.3	16 810
Sleipner A	21.3	33.3	16 810
Sleipner A	21.3	33.3	16 810
Sleipner A	21.3	33.3	16 810
Sleipner T	21	33.3	16 573
Sleipner T	21	33.3	16 573
Sleipner T	18	33.3	14 205
Snorre A / Vigdis	21	35.5	15 546
Statfjord A	15	34	11 594
Statfjord A	15	34	11 594
Statfjord B	15	34	11 594
Statfjord B	14	34	10 821
Statfjord C	17	34	13 140
Statfjord C	15	34	11 594
Tor 2/4 E	4.4	29	3 987
Ula	13.8	34.5	10 512
Visund	18	35	13 515
Åsgård A	29.5	38	20 402
Åsgård A	29.5	38	20 402
Åsgård A	18.5	25	19 447
Åsgård B	29.5	38	20 402
Åsgård B	29.5	38	20 402
Åsgård B	29.8	38	20 609
Åsgård B	18	25	18 922

3.7 Comment

The potential hydrogen utilisation obtained by comparing with industrial energy demands today covered by natural gas (gaseous and liqued) sums to 91 000 t per year. The highest individual consumers are likely connected to Yara’s ammonia production at their Porsgrunn facility, consuming 80 000 t hydrogen annually, and Equinor’s methanol facility at Tjeldbergodden, demanding 130 000 t hydrogen yearly.[19] Further, Equinor’s Mongstad refinery consumes 11 000 t, with potentially TiZir Titanium in Tyssedal also in need for similar yearly quantities. The total potential in the Norwegian industry is then estimated to lie around 323 000 t hydrogen every year. This is at least an order of magnitude more than estimates for the Transport Sector. Clearly, a dedicated political effort is in need if all energy to the industry today covered by natural gas were to be replaced by hydrogen. Following the estimates from the transport sector, a 10% replacement by hydrogen would then project the need of 9 000 t, reducing the total yearly hydrogen consumption by 26%, leaving a net demand of about **240 000 t hydrogen annually** for the industry sector.

Furthermore, it is highly unlikely that all the offshore gas turbines will be converted to H_2 based gas turbines. Assuming a 10-20% conversion, we can say around 10 gas turbines will be converted to using hydrogen as fuel. This represents a demand of around **150 000 t hydrogen** annually for offshore gas turbines.

[19] It should be noted that the hydrogen production for ammonia manufacture and methanol manufacture are done is captive hydrogen plants. That is the H_2 production is an integrated part of the manufacturing process and is not bought from merchant H_2 vendors.

4 POTENTIAL FOR CO_2 STORAGE IN NORWAY

There is considerable CO2 storage capacity in offshore aquifers and depleted oil and gas reservoirs. In fact, a major part of European storage capacity is to be found in sedimentary basins on the Norwegian shelf. The Norwegian Petroleum Directorate (NPD) issued a detailed CO_2 storage atlas[20] that outlines the possibility for storing CO_2 in the North Sea of the coast of Norway. The detailed and comprehensive atlas was made to provide an overview of where it is possible to implement safe long-term storage of CO_2 and how much capacity there is for geological storage of CO2 in the Norwegian part of the North Sea. One objective of the study was to identify locations which could be matured further to be qualified as storage sites. NPD's evaluation gives a total capacity in saline aquifers of 43 Gt CO2 with an additional 27 Gt in petroleum related fields (abandoned fields and fields open for EOR or closure up to 2050).[21] The table below[21] provides an overview of the storage prospects grouped into saline aquifiers and petroleum related fields.

Aquifers Basin/reservoir	Estimated CO_2 storage capacity (Gt)
Utsira and Skade	15.8
Bryne/Sandnes southern parts	13.6
Sognefjord Delta east	4.1
Stratfjord Fm. East	3.6
Gassum	2.9
Bryne/Sandnes Farsund Basin	2.3
Johansen and Cook	1.8
Fiskerbanke	1
Hugin East	0.1
Stord Basin, Jura	0.1
Stord Basin, mounds	0.05
Hydrocarbon fields	**Estimated CO2 storage capacity (Gt)**
Abandoned fields	3
Fields in production 2030	4
Fields in production 2050	6
Sognefjord delta including Troll	14

The Norwegian government plans to develop a full-scale CCS project where CO_2 is capture from 1 or more industrial sources and the CO_2 will be stored in the North Sea. The storage capacity requirement for the full scale project is 1.5 million tonnes of CO_2 per year over a five year period. Equinor, Total and Shell are part of the Northern Lights project to rank and perform a risk analysis of 3 storage sites: Heimdal, Smeaheia and Utsira South. Smeaheia, offering both operational and geological flexibility, has been selected for further maturation as a new off shore CO_2 storage site in Norway.[22]

[20] Halland, E.K. et al. (2011) CO2 storage atlas - Norwegian North Sea. The Norwegian Petroleum Directorate
[21] Anthonsen, K. L. et al. (2013) 'CO_2 Storage Potential in the Nordic Region', Energy Procedia. Elsevier, 37
[22] Ringrose, P.S. et al. (2017), `Ranking and risking alternative CO_2 storage sites offshore Norway´, NEAR SURFACE GEOSCIENCE'17

4.1 Linking CO_2 storage capacity and potential H_2 utilisation

When converting CO_2 from NG anywhere between 7-10 tonnes of CO_2 is produced for every tonne of H_2. Assuming a CO_2 capture ratio of 90%, that would mean that 6.5-9 tonnes of CO_2 will be sent to storage for every tonne of H_2 produced. For the H_2 utilization let us assume:

- the scaled DNV-GL scenario for H_2 utilization in the transportation sector (60 kt/year),
- H_2 as fuel in industry (90 kt/year),
- H_2 as a reducing agent in TiZir Titanium facility (10 kt/year),
- 10 offshore gas turbines (115 ktonnes/year).

The total H_2 utilization is 275 ktonnes/year. The captured CO_2 from H_2 production that is sent to storage will be around 1.8 – 2.5 Mt/year. Given a Norwegian storage capacity of 70 Gt CO_2, this corresponds to a capacity of over 2500 years with this level of H_2 utilisation.

The Norwegian full scale project and the Nothern light project have selected Smeaheia for further development. This storage site is expected to have a capacity in the range 100-130 Mt of CO_2. This has been developed with the initial goal of storing 1.5 Mt CO_2/year from industrial sources. The CO_2 emissions from the potential H_2 utilisation is also in the same range and it is expected that it should be feasible to store emission from H_2 production in the future.