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Building a hydrogen infrastructure in Norway

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Abstract

Hydrogen is expected to become an integral part of the Norwegian energy system in the future, primarily as a fuel for transportation. The NorWays project aims at providing decision support for introduction of hydrogen in the Norwegian energy system by modelling the energy system and hydrogen infrastructure build-up at various spatial levels. GIS-based regional hydrogen demand scenarios and hydrogen refuelling station networks have been generated, considering organic growth of regional hydrogen deployment and increasing density of hydrogen users over time. A regional model was used to optimise supply scenarios for these hydrogen refuelling station networks, including choice of production technology (biomass gasification, NG SMR, electrolysis, by-product hydrogen) and delivery (pipeline, truck, and onsite schemes) as well as integrated hydrogen delivery networks by truck and pipeline. The sensitivity to variations in energy price and GHG emission constraint scenarios on hydrogen production and delivery mix and average hydrogen costs was assessed, and conclusions on the effectiveness of policy measures were drawn.

Keywords: hydrogen, infrastructure, optimization, modeling

1 Introduction

Norway is a sparsely populated country in Northern Europe with abundant fossil and renewable energy resource potentials. Thus, security of supply is not a major driver for introduction of hydrogen in the Norwegian energy system. Other characteristics of the energy system, however, set certain constraints for the development of a hydrogen infrastructure, such as the absence of a natural gas (NG) distribution grid, despite Norway being the world's third largest natural gas (NG) exporter. However, the following pre-requisites make introduction of hydrogen as a transportation fuel in Norway especially attractive:

- High GHG emissions from transportation due to sparse population
- Stationary power generation and a large share of the heating demand are covered by hydropower, thus, a proportionally higher share of GHG-emission reductions must be realised the transportation sector
- High untapped potential of wind power for renewable hydrogen production

- Abundant NG resource and suitable formations for CO_2-storage in the North Sea providing a substantial potential for large-scale production of CO_2-lean hydrogen
- High taxes on new vehicles leaving an extra degree of freedom for efficient policy measures (tax exemptions etc.) to support introduction of hydrogen vehicles
- Considerable R&D and industry competence and skills, especially within petro- and electrochemistry as basis for substantial value creation.

Based on these premises, Norway has the potential to become a pioneer in hydrogen supply and infrastructure technologies development as well as an early adopter for utilisation of hydrogen as energy carrier.

A national roadmap project was initiated in 2006 with the objective of providing decision support for introduction of hydrogen in the Norwegian energy system. The project entitled NorWays includes modelling at national, regional and local level, utilizing energy system modelling (MARKAL), Well to Wheel-studies and infrastructure analysis. The work is carried out on the basis of and in close cooperation with the EU hydrogen roadmap project HyWays [1].

Planning of a regional infrastructure development constitutes a major part of the NorWays project and the results from this activity are reported in this paper. Due to the size and diversity of the country, there was need for regionalized modelling of both hydrogen demand and supply build-up. Outcomes are realistic and economic hydrogen infrastructure development scenarios until 2050 as well as statements on primary energy used for hydrogen production, supply schemes, costs and GHG emissions. Using scenario analyses, statements on the impact of energy prices and policy measures on these key results can be derived. A detailed description of approaches and results is given elsewhere [2].

2 Methodology and Assumptions

Many authors have described spatially detailed models and studies for the build-up of hydrogen infrastructures for countries or world regions [3,4,5,6,7]. Approaches range from pure economic optimization of spatial demand and supply to heuristic allocation of demand and supply schemes to different purposes and region types [3]. The infrastructure build-up problem can generally be split into a demand and a supply side [5,8], which can be analysed consecutively assuming exogenous demand.

The highest demand for the fuel will under pure market conditions arise where the cheapest fuel can be supplied. However, aspects like a sufficiently high demand for transportation, the willingness of the users to switch fuel, innovativeness of a region and political aspects, and the visibility of the innovation technology should be respected as well. The model optimisation freedom on the demand side should therefore be confined with realistic bounds, taking into account regional aspects as well as various market segments [8].

For the supply side, the main question to answer is which production (feedstock, plant sizes, locations, etc) and delivery schemes (e.g. pipeline transport, truck transport, onsite production) will be most advantageous with respect to costs, and furthermore flexibility and investment risk. Certain bounds may apply, as e.g. restrictions in feedstock availability.

The approaches used for modelling demand and supply side, and the key approaches and assumptions are described in the following sections.

2.1 Regional Hydrogen Demand and Refuelling Station Siting

2.1.1 Overall Exogenous Hydrogen Penetration

The shares of different power trains for passenger cars were estimated based on the assumption that the transportation sector needs to cut down emissions by 75% from 2005 to 2050 in order to reach the Norwegian GHG reduction targets. While biofuels are mainly allocated to goods transport, the reductions in private transportation are expected through CO_2-free electricity and hydrogen. The penetration of hydrogen vehicles is assumed to start by 2010 and reach 70% by 2050 (see Fig. 1). To achieve this, from 2040 all new cars sold must be either hydrogen (70%) or battery (30%) powered.

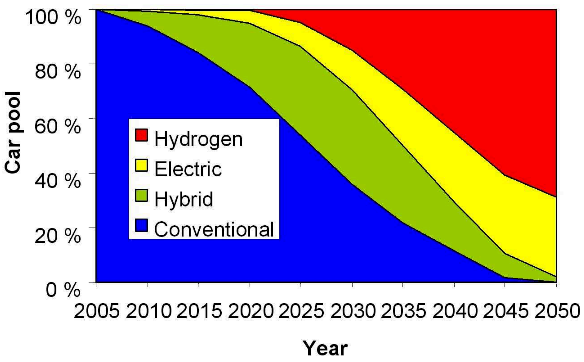

Figure 1: Estimated share of passenger vehicles in car pool (“Scenario B” [9]) as basis for the infrastructure assessment reported here.

2.1.2 Early user centres

Following the HyWays approach [8], it is assumed that the regional use of hydrogen in Norway will be initiated in population centres, ensuring high initial infrastructure utilisation, visibility and an innovation-friendly customer base. For the infrastructure analysis, it is chosen that Oslo will be the first user centre from 2010, and Stavanger, Grenland, Bergen and Trondheim will follow from 2020. Furthermore, the NorWays project partners have chosen to analyse Oslo, Stavanger, and Grenland region with a regional MARKAL model, based on a number of indicators [10]. The MARKAL-results are reported separately/elsewhere.

2.1.3 Organic growth of local hydrogen use

After being initiated in the early user centres, the hydrogen use is assumed to grow by extent and intensity. New regions to be deployed are selected by multi-criteria analysis (criteria are population density, car density, purchasing power and neighbouring regions with hydrogen supply). Assuming equal share of new hydrogen cars among new car sales in all regions with access to hydrogen, the local vehicle penetration and hydrogen demand are determined recursively to achieve the overall penetration curve (Fig. 1). From 2040 on, all regions have access to hydrogen, yet with different local vehicle penetration rates. The resulting deployment of hydrogen is shown in Fig. 2.

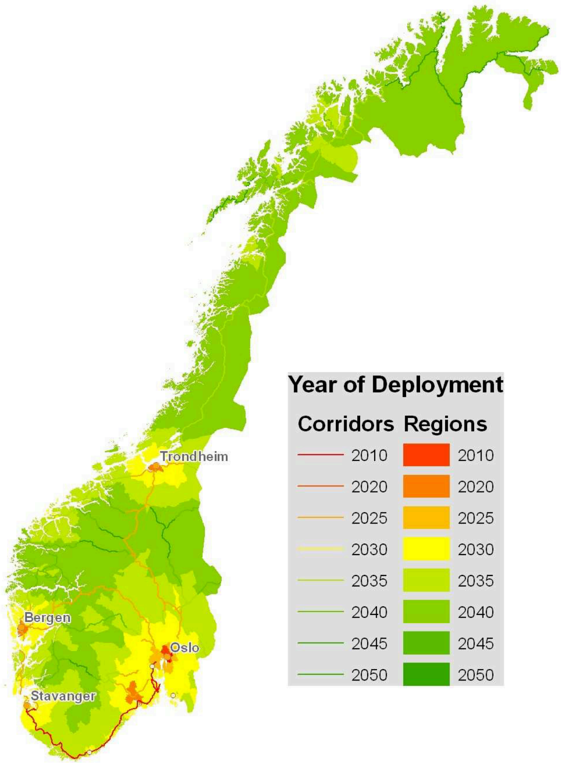

Figure 2: Year of hydrogen deployment in Norwegian municipalities and corridors

2.1.4 Selection of refuelling stations

A last step on the demand side is to select refuelling stations in every supplied region where hydrogen is dispensed, and estimate how much hydrogen will be dispensed at each station. First, a given total number of hydrogen refuelling stations (HRS) ranging from 46 by 2020 (avg. 500 vehicles per station) to 1100 by 2050 (avg. 1600 vehicles per station) is distributed to the regions in a way to minimize the average vehicle-to-station distance. Then, within each region individual refuelling stations are selected and their hydrogen turnover calculated by cluster analysis of existing “conventional” refuelling stations.

2.1.5 Corridors

Additionally to local HRS, corridors are needed to connect the early user centres and adjacent regions with high traffic exchange (e.g. commuting, recreational areas) to enhance user acceptance. Corridor refuelling stations must have a certain mesh density (typically ~50 km) to allow for convenient refuelling and, thus, these need to be considered separately and differently. Here, the hydrogen demand along the corridors is estimated with a traffic density model based on the reciprocal distance of a corridor segment to the local hydrogen user centres and their intensity.

With the described methodology, a regional demand and HRS build-up scenario from 2010 to 2050 was developed. Fig. 3 shows the hydrogen demand landscape in the year 2035 (including local use, corridors, and HRS).

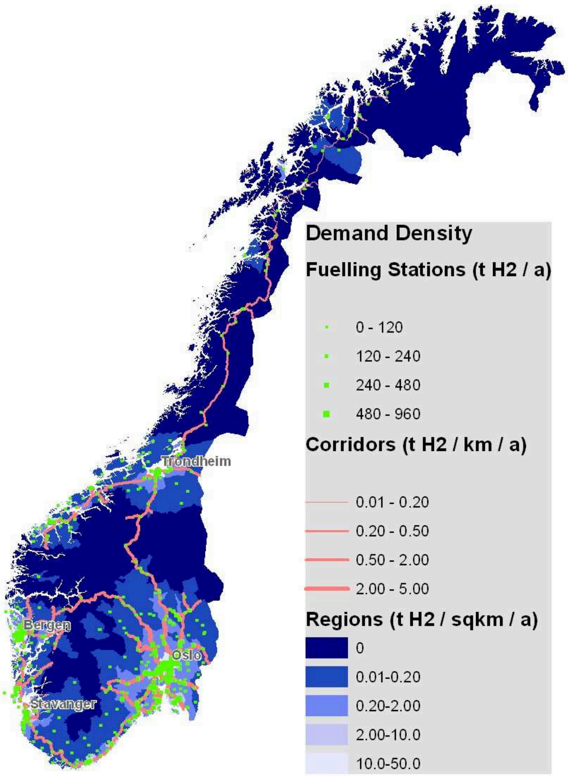

Figure 3: Hydrogen demand in Norway 2035

2.2 Regional Hydrogen Supply

Once the hydrogen demand scenario has been designed, the next step is to calculate how the hydrogen is supplied to the refuelling stations at least cost.

The following options are considered for hydrogen production at the following process capacities (metric tons of hydrogen per year):

- Central NG SMR (3600 t/a w/o carbon capture; 67,000 t/a with and without carbon capture)
- Central biomass gasification (12,000 and 60,000 t/a)
- Central electrolysis (580 t/a per module)
- Onsite electrolysis (16, 120, 480 t/a)
- Onsite NG SMR (120, 480 t/a)
- By-product hydrogen from existing plants (replaced by NG).

It is assumed that electricity is available everywhere, biomass only in South and Central Norway, and NG only at the population centres at the south and west coast.

The following hydrogen delivery options from central production to the HRS are considered:

- Pipeline (12"; maximum delivery 7200 t/a, minimum spanning tree architecture)
- Gaseous hydrogen truck (star-like routes, full trailer exchanged against empty at the refuelling station; delivery 0.45 t/trailer; avg velocity 50 kph, accounting road network distances)

The NorWays partners have chosen not to consider liquid hydrogen transport an option for Norway.

The HRS consists of a number of dispensers modules (120 t/a) for 70 MPa gaseous hydrogen (including compression and high pressure storage). Techno-economic data are mostly taken from the HyWays project [1].

To optimize the supply structure, the H2INVEST model has been developed [11]. For a given list of HRSs (location and hydrogen demand through the analysis time), at each time step the model evaluates building central plants at a list of specified locations and delivering the hydrogen to the best suited stations, with onsite hydrogen production being the fallback option. Total scenario costs and HRS-specific hydrogen supply costs are calculated from capital costs (annuity), operation & maintenance and energy costs. Based on a greedy algorithm, the model first implements the plant which decreases total costs the most, then the second most, etc, until no further cost decrease is achieved – just as an investor would do. This procedure is repeated for each time step (2010 to 2050 in 5-year steps), where once-built central plants and pipelines persist until end of life is reached. In contrast, onsite production equipment is transportable, and must not persist at a given location.

The energy prices assumed for the supply optimisations (base case) are shown in Fig. 4. In addition, a CO_2 quota price of 25€/ton emitted was assumed. For all options including utilisation of electricity, Norwegian electricity mix was assumed, consisting of >99% hydropower with corresponding very low specific GHG emissions.

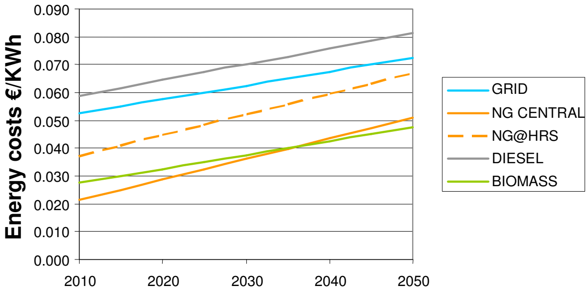

Figure 4: Assumed prices for grid electricity, NG at central production and HRS sites, diesel fuel, and biomass.

3 Results and Discussion

With the H2INVEST model, six supply scenarios have been simulated; a base case and 5 derivations.

The hydrogen supply landscape in 2035 in the base case scenario is depicted in Fig. 5 (corresponding to the demand in Fig. 3, and including production facilities, truck and pipeline routes, and onsite generation). The hydrogen costs at the pump resulting from this supply scenario (including proportionate costs for production, transport, and the refuelling station) are shown in Fig. 6. The hydrogen costs depend on the utilisation/turnover of the station, the production and delivery method and the delivery distance. As expected, hydrogen tends to be cheap in the population centres with large HRS and when central SMR dominates production. On the other hand, in less populated areas hydrogen is produced onsite by electrolysis at higher specific costs, and moreover the turnover is lower, which leads to increased specific hydrogen costs at these stations.

Other scenarios studied include lower electricity prices, higher CO_2 prices, higher oil and gas prices, better biomass gasifiers (higher efficiency; lower costs) and limitations of truck delivery frequency. Results of these scenarios are shown in detail in the respective deliverable of the NorWays project [2].

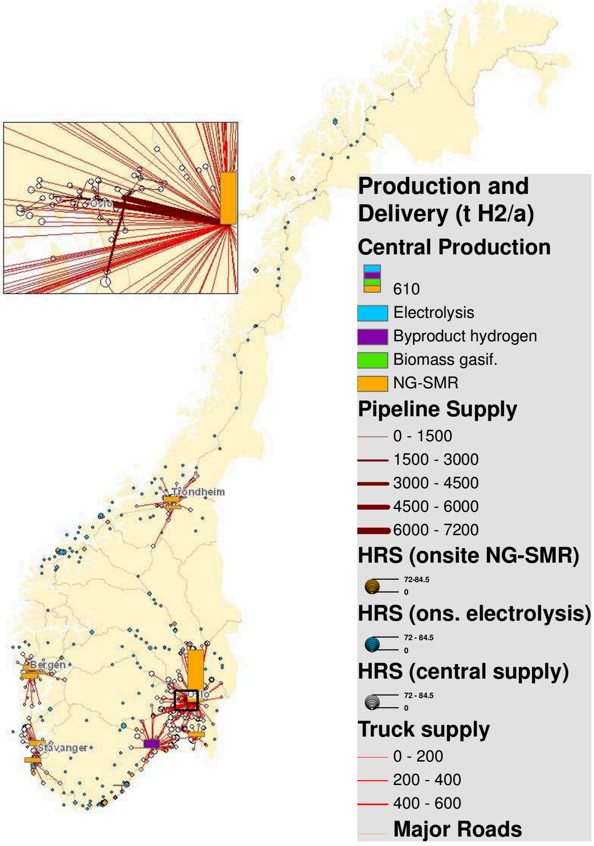

Figure 5: Hydrogen supply in Norway 2035

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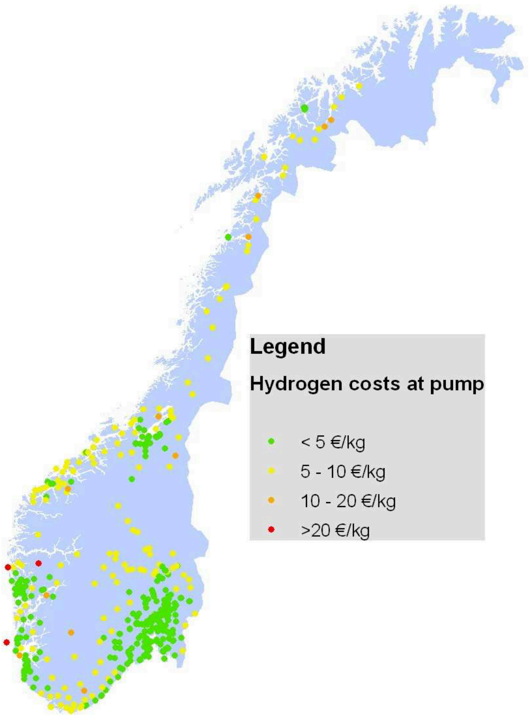

Figure 6: Resulting hydrogen costs at the pump 2035

In addition to the inventory lists discretised over time and space and GIS output data (see Fig. 3), the H2INVEST model returns aggregated shares of hydrogen production, delivery, costs and specific GHG emissions. For the base case scenario, these aggregate main results are shown in Fig. 7. Resulting average GHG emissions (Well-to-wheel basis; assuming fuel cell vehicles with hydrogen consumption of 0.7 kg/100 km [1]) and hydrogen costs at the pump for all studied scenarios are shown in Fig. 8.

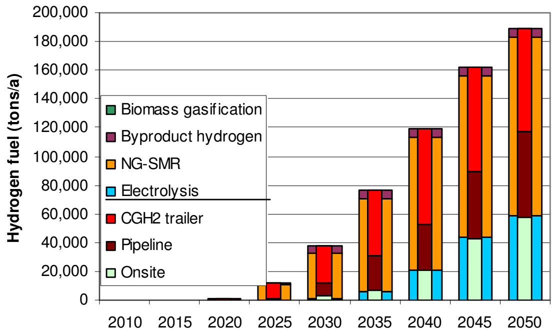

Figure 7: Production (outer bars) and distribution (inner bars) of hydrogen in the base case scenario

Under the energy price and equipment cost assumptions taken and considering topology and available production and supply options, hydrogen will in the base case beyond 2020 mainly come from central NG SMR (without carbon capture) and onsite electrolysis, with the latter gaining momentum beyond 2035 when the sparsely populated areas are deployed and NG prices increase. Byproduct hydrogen is used where available, while biomass gasification and SMR with carbon capture do not appear economic under current assumptions.

The delivery is strongly centralised in the higher populated South, with truck delivery being gradually shifted to pipeline delivery in the later years. The sparsely populated and Northern areas are mostly supplied with onsite electrolysis.

Before 2025 the low capacity factors of the transport and HRS boost the specific costs, however the total annual costs are rather low. From 2025, the hydrogen costs reach a competitive level below 5 €/kg in all scenarios, with energy costs henceforth playing an increasing role due to assumed price increases.

Well-to-wheel GHG emissions in the base case range down from 63 g/km by 2030 to 32 g/km by 2050, the highest contributor being NG SMR without carbon capture.

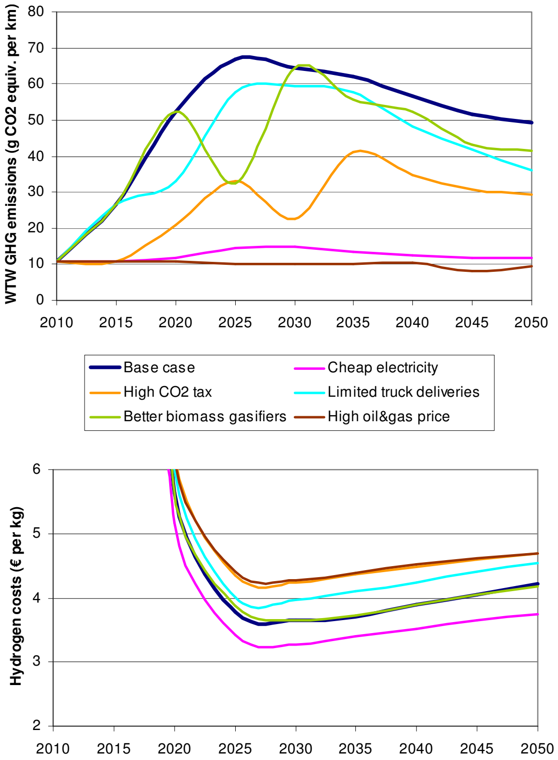

Figure 8: GHG emission and cost results of the scenario analysis

The scenario analysis reveals the following variations from the base case:

- Cheap electricity (reduced by 1.8 ct/kWh) induces a substantial shift towards hydrogen from electrolysis. The only other option employed is by-product hydrogen. Virtually no pipelines are built; all centrally produced hydrogen is transported by truck. The virtually CO_2-neutral electricity employed for electrolysis makes that the per-km GHG emissions are at a constant low level. The overall annual costs are slightly reduced, with the share of energy costs increasing.
- High CO_2 tax (100€/ton) shifts the optimum towards more onsite electrolysis, which in Norway is virtually CO_2-neutral. The contribution of NG-SMR is reduced accordingly. This leads to a reduction of GHG emissions of hydrogen vehicles to 30 g/km by 2050. Average annual costs are about 10% higher than the “Base case”, mostly since more expensive energy must be purchased and the CO_2 expenditures now make about 10% of the overall costs.
- Limiting truck deliveries to HRS (max 180/year) diminishes the contribution of trailer transport to below 8% from 2020 and onwards. Accordingly, the shares of pipeline

delivery and onsite electrolysis increase. This leads to an enhancement of the electrolysis share to app. 60% by 2050, while the contribution of NG SMR is somewhat lower than in the "Base case". GHG emissions are reduced to about 35 g/km driven by 2050, while the costs increase by about 5% against the "Base case".

- Assuming better biomass gasifiers (-60% investment; -20% biomass consumption) causes that a smaller plant is built by 2025 (then contributing 50% of the overall hydrogen production). By 2045, the next investments are made, and by 2050 approximately 20% of all hydrogen is produced from biomass. Compared to the "Base case", this leads to a reduction of app. 10 % points from electrolysis and central NG-SMR, respectively. The GHG emissions are only reduced to about 42 g/km driven by 2050. Only slight reduction of total annual costs and specific hydrogen production costs occurs.
- The scenario with constant high oil and gas prices (oil 200 USD/bbl; NG 163USD/boe) returns a supply landscape similar to the "Cheap electricity" scenario, namely a strong shift to onsite electrolysis. Also central electrolysis in combination with truck transport has a small share (about 5%) in areas where few HRS can share production equipment by this way. Towards 2050 investments in biomass gasifiers are done, which then produce about 30% to hydrogen. The GHG emissions at a constant low level over the whole analysis period. Costs increase by about 10% compared to the base case.

4 Interpretation and Conclusions

The current paper analyses scenarios for hydrogen demand and supply build-up in Norway until 2050. In all scenarios, decentralised production technologies, especially electrolysis, play a crucial role due to Norway's low population density. The costs of hydrogen can be at a competitive level from a penetration rate of app. 5% (anticipated in the year 2025). Greenhouse gas emissions from hydrogen production depend on the production mix and can be influenced effectively by political measures such as a high CO_2 taxes or subsidies on renewable electricity. The H2INVEST model analyses least-cost hydrogen supply to a set of HRSs and is a flexible tool to study realistic regional infrastructure build-up and the impacts of various input parameters.

4.1 Role of production technologies

Out of the scenario results, the following roles can be derived for the different hydrogen production technology options in Norway:

- **Onsite electrolysis** dominates production in many scenarios and during the whole analysis times, with shares varying between 20% and 95%. Onsite electrolysis plays a special role in Norway due to the sparse population, the virtually GHG-neutral grid electricity, and also the expertise Norwegian industry has in electrolysis.
- **Onsite SMR** plays a very limited role in Norway, primarily due to the absence of a NG distribution grid: In sparsely populated areas, due to the limited NG availability and relatively cheap electricity, electrolysis is better suited. In densely populated areas, central supply is the cheaper option in most cases. Onsite SMR may play a role at central HRS locations with high demand, NG available and where truck delivery is limited, as long as pipelines are not an option.
- **Central SMR** plays an important role in most scenarios in the mid-to-long term (except scenarios with cheap electricity and high oil&NG prices). The first plants are built after 2020 in southern locations with high population density. By 2050 between 30% and 65% of the hydrogen is produced by central SMR. Reformers with carbon capture are not chosen in any of the scenarios, since CO_2 can only be injected at few locations, and other GHG-lean options seem to be more economic.
- **Central electrolysis** plays a limited role in Norway (<5%), because in most situations either onsite electrolysis or other central options are more economic. Central electrolysis may be applied in small cities where a few adjacent HRS can be supplied, but the overall demand is too low to e.g. build a central SMR plant.
- **Byproduct hydrogen** plays a limited but firm role in all scenarios (from up to 70% by 2020 to below 4% by 2050). Especially the plant at Rafnes is very attractive, since it is located close enough to the HRS in Grenland to allow for pipeline distribution, and furthermore Oslo can be supplied by gas truck.

- **Biomass gasification** is not competitive in most of the scenarios under the cost and performance assumptions taken. Only if the biomass gasifier with substantially higher efficiency and lower costs are realised, or high oil & NG prices are assumed, biomass gasification is penetrating the hydrogen production with a contribution of 20%-30% by 2050. The gasifiers are restricted to south and central Norway, and are likely to be built close to medium and larger cities with sufficient demand.

4.2 Role of delivery technologies

From the scenario results, the following roles can be derived for the different hydrogen delivery technologies in Norway:

- **Onsite production** plays a strong role in most scenarios, especially in Norway's sparsely populated areas where central supply schemes imply long transport distances.
- **CGH_2 trailer / truck delivery** is suited for smaller to medium hydrogen demand stations which are relatively close to a central production location (less than 100 km), especially for by-product hydrogen during the early phase. For the stations with very low demand, trailer delivery cannot compete with onsite electrolysis due to the high investment in onsite storage trailers which are needed for swapping. In the middle term, up to 90% of the hydrogen produced is delivered by truck. By 2050, the share is reduced to 20-45%.
- **Pipeline delivery:** For short distribution distances and high volumes, i.e. HRS in higher populated areas, pipeline delivery can be the most economic delivery option. In most scenarios pipelines start to develop between 2025 and 2030 (firstly in the Oslo area), and by 2050 about 10-40% of all hydrogen produced is delivery via pipeline.
- **LH_2 truck delivery:** This technology has by consent of the partners not been assessed in this study. LH_2 trailers allow for economic transport of hydrogen across longer distances, however at the cost of a high liquefaction energy effort. If LH_2 trailers were considered, they would most likely displace onsite production in the South where the distance to the central plant location is not larger than 300-500 km. In the north of Norway, where NG availability is currently and also in this study restricted to only one location (Melkøya), the largest part of the HRS would probably still be supplied by onsite electrolysis.

4.3 Recommendations for politics and industry

Once established and sufficiently utilized, an area-wide hydrogen infrastructure in Norway seems to be cost competitive with the conventional fuel infrastructure, especially when considering the significantly lower fuel consumption in fuel cell vehicles. However, when trying to implement larger changes in society the initial phase is troublesome. Even though the commitment of industry is high, the first years of getting the infrastructure roll-out started are unprofitable and industrial player are presumably not ready to cover the risk alone. Furthermore, the chicken-and-egg problem needs to be solved both from the side of the car manufacturers/drivers and the infrastructure providers. To make the hydrogen story a success, the infrastructure roll-out cannot only happen by cherry-picking the most profitable refueling locations, but also some less attractive stations need to be opened to provide the early drivers with sufficient network coverage, and the high costs accruing at these stations cannot be forwarded to the customers.

We therefore recommend the following actions:

- **A joint initiative of infrastructure and automotive players should be established**. This is the most elegant remedy for the chicken-and-egg problem. Utilization of capacity and refueling opportunities can be best optimized by a concerted action, i.e. both parties create a common roll-out plan, starting with few regions and then expanding gradually.
- **An instrument for cost leveling should be created.** The huge cost differences between the refueling stations need to be equalized. This can e.g. happen through a fund where the cost-effective refueling stations pay into, and the cost-ineffective refueling stations receive support from.
- **Early subsidies are required to pass the valley of death.** Especially in the early phase, the relative hydrogen costs will be high and hence this phase will not be profitable for the players. However, the overall costs which have to be covered are relatively low. Our analyses have shown that between 2010 and 2020, the overall infrastructure costs of an

early hydrogen infrastructure in Norway accumulate to app. 50 million €. Governments should diminish the risk for early players in order to trigger investment decisions. Therewith the infrastructure build-out would be significantly accelerated, and break even could be achieved sooner. To meet the pace of the build-out described here, an effective bundle of policy measures needs to be in place from 2010.

- **Selective policies should be put in place to control the infrastructure build-out.** Framework conditions are crucial to influence the way a hydrogen supply infrastructure develops. E.g., providing grants for renewable electricity used for hydrogen production, or charging CO_2 emission penalties, can significantly change the picture towards a more CO_2-lean production mix. Other ways to influence hydrogen production mixes are technology-specific one-time subsidies, or selective per-volume subsidizing hydrogen depending on the technology/feedstock used for its production. Moreover, one-time subsidies for every new station could be a means to trigger the build-up of a suitable number of hydrogen stations.

Nomenclature

GHG	Green house gases
GIS	Geographic Information System
NG	Natural Gas
SMR	Steam Methane Reforming
WTW	Well-to-wheel
CGH_2	Compressed gaseous hydrogen
LH_2	Liquid hydrogen
HRS	Hydrogen refuelling station

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