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1 Introduction, Scope and Methodology

A hydrogen refuelling infrastructure is more complex than other fuel infrastructures due to the number of technology options, the site- and volume-dependent cost structure, the varying CO_2 emissions burden depending on hydrogen source and the risks and conflict of interests of the players involved. Market economics alone cannot lead to a successful breakthrough of this technology; a coordinated and concerted approach is needed for the early introduction.

A case study has been conducted to realistically simulate the build-up of hydrogen use in transportation and refuelling infrastructure in the Greater Oslo Area in Norway. The H2INVEST model was used to simulate the hydrogen infrastructure and to perform business analyses for the region. The model creates sets of refuelling sites allowing for maximum user convenience, estimates the hydrogen demand at these locations over time, and creates cost-optimum spatially and timely discrete production and distribution infrastructure to supply the hydrogen to the sites, respecting potential policy measures. [1]

Then, these results were utilized for a detailed business analysis, focussing on the five stations with highest and lowest demand, respectively.

The paper highlights key results of the case study in terms of refuelling station build-up, hydrogen supply infrastructure and subsidy models. Conclusions will be drawn on the requirement of subsidies and levelling mechanisms between high- and low-demand stations.

2 Hydrogen Demand and Refueling Station Rollout

The case study is based on modelling the spatial distribution of the infrastructure and its development over time. In 2008, the Greater Oslo Area (GOA) had about 980,000 inhabitants. It is assumed that the users of the cars live in the GOA, while they may drive to places outside; i.e. hydrogen refuelling stations can also be located outside GOA which also holds for hydrogen production locations. The analysis timespan covers 2010 to 2025 in one-year steps.

We have assumed that mass roll-out of hydrogen fuel cell vehicles commences in 2016-18 and that by 2025, about 60,000 hydrogen vehicles will be registered in the area, beside private cars also comprising about 100 public city buses and fair numbers of multi-purpose vehicles and delivery vans. A total hydrogen demand of app. 6,000 tons/year was projected for these vehicles by 2025. The vehicles were distributed over the municipalities of GOA following deployment logics at regional scale (i.e. a municipality which is connected later will

[1] For a detailed description of the methodology used to calculate demand, locate refuelling stations and optimise the hydrogen supply infrastructure in the H2INVEST model, refer to www.H2INVEST.com

gradually catch up in penetration with municipalities connected earlier). The number of refuelling stations in the area was assumed to reach a level of 20-30 by the year 2020 and then remain constant until 2025 (with the average hydrogen turnover per station continuously growing). The stations were assigned to the municipalities respecting the area and the local vehicle population. Then, to place the hydrogen stations within each municipality, a subset of conventional refuelling sites was chosen. It was distinguished between hydrogen demand for local, highway and public fleet driving. Conventional refuelling sites along high traffic roads were preferred in general while at the same time a widespread distribution of HRSs across the analysis region should be achieved.

With a set of 30 stations, an average travel distance to the next refuelling station of 3.4 km is achieved (assuming vehicles and HRS to be equally distributed over the municipalities). By reducing the number of HRS to 20, this distance increases to 4.1 km. Finally, the hydrogen demand at the stations was estimated by means of a simple distance-related traffic model and scaled by the traffic passing by each station.

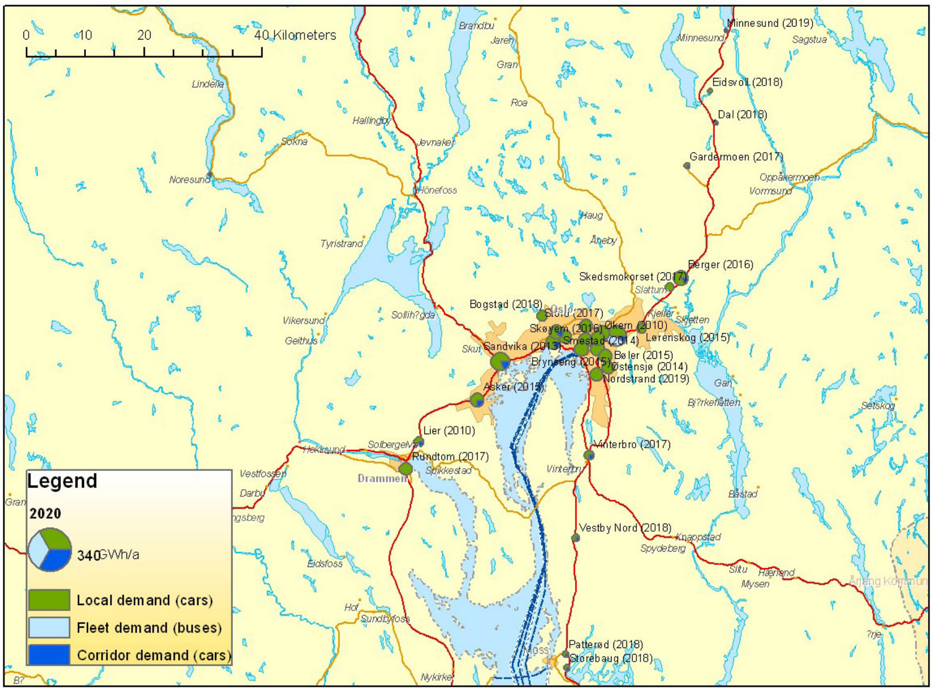

Figure 1: Selected hydrogen refuelling locations and calculated hydrogen demand 2020.

Figure 1 shows the selected hydrogen refuelling station locations and the estimated hydrogen demand at each station by 2020 (30 stations). Stations in the centre encounter the highest demand due to high traffic density than in remote locations. Four standard station equipment types were defined with capacities of 25, 300, 1,000, and 3,000 kg/day. Once the demand at a station would exceed the current capacity, the current equipment would be removed (to be installed at a new site, either within the same area or in other areas), and the next larger equipment type would be installed.

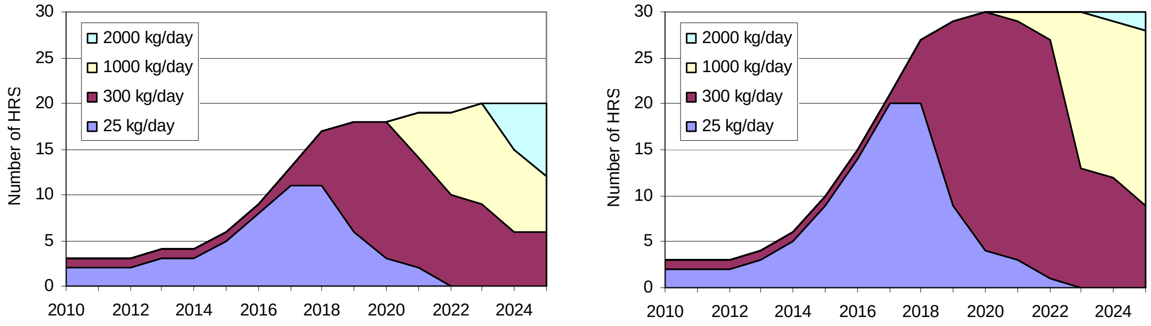

Figure 2: Split of HRS types over time (left: 20 stations; right: 30 stations).

Figure 2 depicts how the HRS type split changes over time for scenarios with 20 and 30 stations. It can be seen that 1/2 (20 HRS) and 2/3 (30 HRS) of the lowest capacity station equipment is required between 2016-18 when the hydrogen turnover is low in order to create customer convenience. For economic reasons this is unfavourable for the retailers since such stations require high investments and yield low revenues. The initial investment in small HRS is not lost as it is assumed that the equipment will be used at more remote locations later (outside the analysis region) afterwards. Yet, in order to avoid early investments in a large number of specifically costly small HRS an option is to install higher capacity equipment earlier though initially heavily underutilized. Although this would result in higher initial costs they are likely to be overcompensated by savings for avoided new installation costs after a few years.

3 Hydrogen Supply Infrastructure Build-up

With the H2INVEST model [2], cost optimized production and transport infrastructure scenarios were calculated to supply the above set of refuelling stations with the hydrogen demand estimated. Relevant hydrogen production options defined were electrolysis (central & onsite), central steam reforming of NG and biogas, and biomass gasification, and a set of industrial locations for the placement of these production plants were specified.

As hydrogen delivery options truck-based distribution of vessel bundles, tube and liquid trailers or pipeline distribution were chosen. Also, short pipelines between adjacent stations to jointly utilize onsite generation equipment were foreseen to form local clusters. The techno-economic data of the production and transport equipment were mainly taken from [3] and [4]. Data on electrolyser and refuelling equipment came from Statoil. The energy prices assumed can be seen in Figure 3. Natural gas and conventional fuel prices rely on a constraint fossil resources scenario [1].

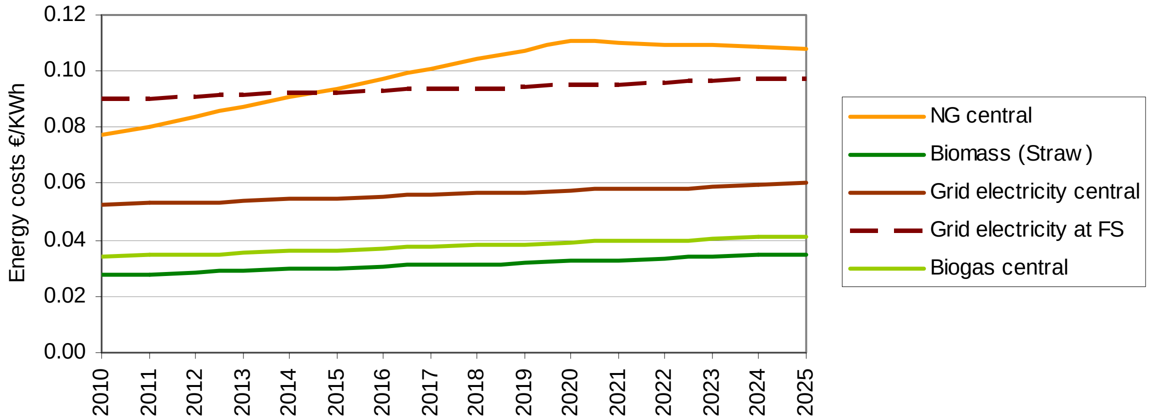

Figure 3: Energy prices assumed for scenarios.

Out of these options, the H2INVEST model calculated integrated supply infrastructure scenarios, choosing hydrogen production locations and production equipment as well as the distribution mode to the set of pre-defined hydrogen refuelling stations. The optimization objective for each time step is to supply the entire hydrogen demand at minimum annual costs. Figure 4 shows the resulting hydrogen production and distribution infrastructure by 2024.

Aggregated results of the hydrogen production and distribution in GOA for the scenario with 30 stations can be seen in Figure 5. For 2010 to 2015 the model suggests to supply most HRSs with by-product hydrogen from a nearby chlorine-alkali-electrolysis plant by tube bundle trailers, which, due to the low total demand, turns out to be the cheapest option during this phase. Only the HRS for buses has a higher hydrogen throughput and is supplied by tube trailer, representing about 80-90% of the overall hydrogen demand in that period.

By 2017, a biogas based SMR is installed, and all hydrogen is supplied from there by truck. By 2020, more biogas reformers are added, and due to the increasing hydrogen turnover, the majority of the HRS is supplied by tube trailers. By 2022, a further demand increase causes a radical shift in the infrastructure, since the limited regional biogas potential available for hydrogen is exceeded. Electrolysis is added to the production portfolio, and most central HRS locations switch to pipeline supply (see also Figure 4). Two onsite electrolysers are built.

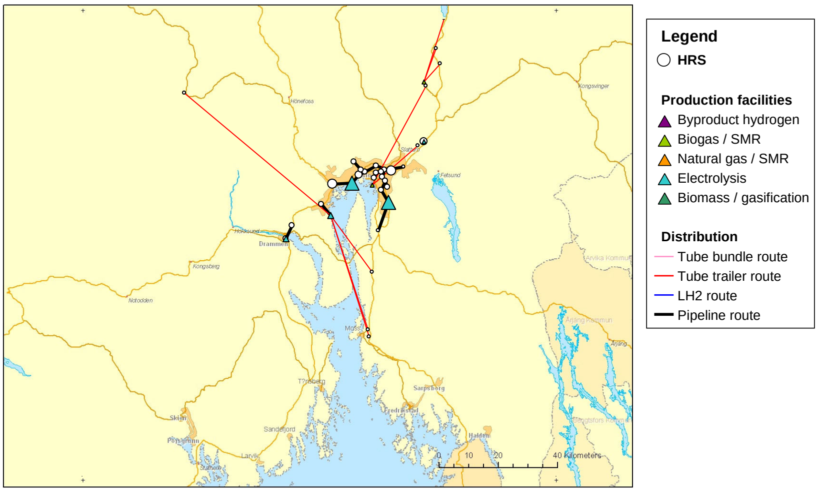

Figure 4: Production and distribution infrastructure for Oslo (30 stations; 2024).

After 2022 the infrastructure does not change further radically. The increased demand is mostly supplied by new electrolysis capacity, and the pipeline grid is expanded by a few branches towards HRS locations at the city border to replace shorter truck routes.

NG-based SMR and biomass gasification were not chosen due to the high feedstock price assumed for NG, and the low efficiency and high electricity consumption assumed for the biomass gasification plant. Likewise, LH_2 distribution is not used in any of the scenarios, since it is typically beneficial for larger distances. LH_2 had most likely become a preferred option if a larger supply region had been analysed.

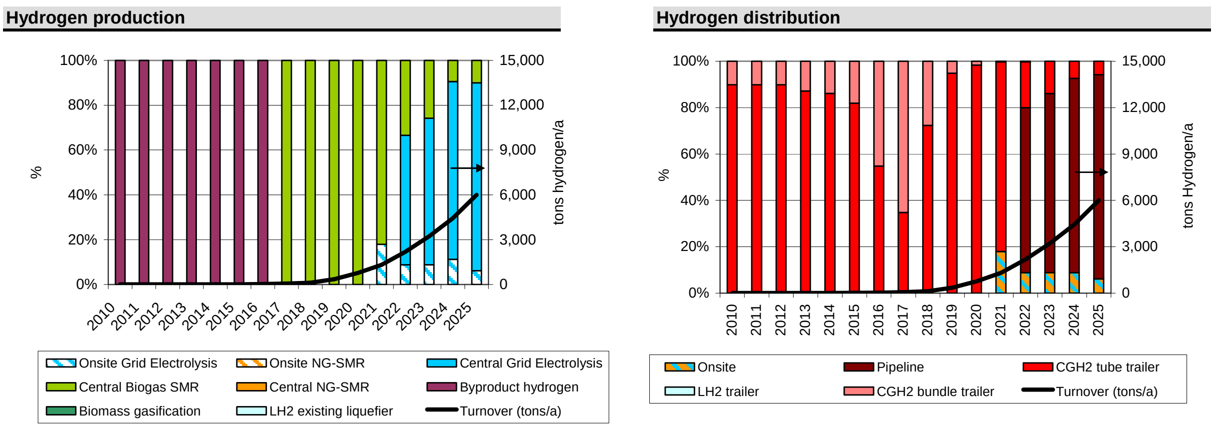

Figure 5: Aggregated hydrogen production and distribution (30 stations).

In the scenario with only 20 stations, the resulting infrastructure roll-out is very similar. However, electrolysis and pipelines are chosen about 2 years earlier than for the 30 station option (Figure 5) which results from the higher turnover per station, a major decision criterion for the hydrogen distribution type.

As a consequence from the use of biogas and electricity (which in Norway is practically greenhouse gas neutral due to the large percentage of hydropower in the electricity mix), the resulting well-to-wheel GHG emissions for fuel cell cars are very low from 2017 and onwards, reaching a CO_2 equivalent level of below 20 g/km. The introduction of hydrogen mobility in Oslo as specified here can cumulatively save about 300,000 tons CO_2 equivalent until 2025.

4 Business Case Analysis

The simulation results from above were used for a detailed economic evaluation of the refuelling stations and the hydrogen infrastructure. In particular, the H2INVEST business tool allows for clustering single infrastructure elements into business divisions and specifying transfer prices for hydrogen between divisions and players defined. With these inputs, major economic parameters such as operating income, cash flow from investments and capital structure are calculated for each division. The clustering process can be structured by the position within the value chain (production-conditioning-distribution-refuelling), being either technology- or location-specific. Financial results can be generated for each business division.

For this study, we assumed two major types of investors. One investor (one independent business division) is responsible for the entire production and transportation of hydrogen to the HRS, regardless of the technology. Furthermore, every HRS is one business division, assuming the HRSs to be economically independent from each other. The transfer price for hydrogen deliveries between the production division and HRSs is site-specific and includes both operating costs (i.e. variable and fixed operating and maintenance costs as well as energy costs) and capital costs (i.e. debt interest and cost of equity). The consumer price at the HRS, however, is calculated as gasoline equivalent and is exempt from fuel taxation until 2020. From 2021 to 2025, we assumed taxation to ramp up to per-km parity with conventional fuel, reducing the net price received by the refuelling station. In addition we assumed the following:

- Working capital requirement for each technology is 5% of the initial investment.
- Declining balance depreciation is used for every infrastructure element.
- Debt ratio is 20% with 9.5% interest on average and 12% costs of equity for all investors.
- Division tax is 30%.
- No extra overhead for infrastructure planning and no inflation.

The profitability of the HRS was assessed based on site-specific net present values (NPV) as a sum of the corresponding discounted free cash flows. The final free cash flow at the end of the analysis timeframe contains the remaining book value of the corresponding equipment in order to account for the terminal value of each station in a conservative way. Figure 6 (left) shows the NPV results for the five HRSs with highest demand (in central, heavily travelled on areas) and five HRSs for lowest demand (in rural areas, which are required for customer convenience), respectively. It can be seen that while for the high-turnover HRSs, the NPV increases from 2020 to 2025 and two stations yield a positive result by 2025, for the low-turnover HRS the NPV decreases even further during this period. This is because the latter have higher specific hydrogen costs and through the beginning fuel taxation, the net retail price is strongly reduced.

We also calculated a case with a one-time investment subsidy upon erection of a new refuelling station of 1.5 million € for HRSs erected by 2010, reduced by 10% each subsequent year (see Figure 6 right) in order to ensure adequate profitability for all stations. With this subsidy, the 2020 NPV is levelled out to a positive value for all HRSs. However, by 2025 the high-turnover HRSs have a high NPV, while for the low-turnover HRSs, the NPVs have decreased to a value near zero. This is also due to the specific hydrogen costs. Moreover, because the high-turnover HRSs are generally erected earlier than the low-turnover HRSs, the high-turnover HRSs receive more subsidies, and the NPV difference in 2025 is higher than without subsidies. A fair subsidising scheme must therefore not only consider the year of erection but also the site particularities (such as traffic and population density). Yet, the delay of the late stations must be taken into account; assuming a further increase in turnover, some years later also the low-turnover stations would probably yield positive NPVs.

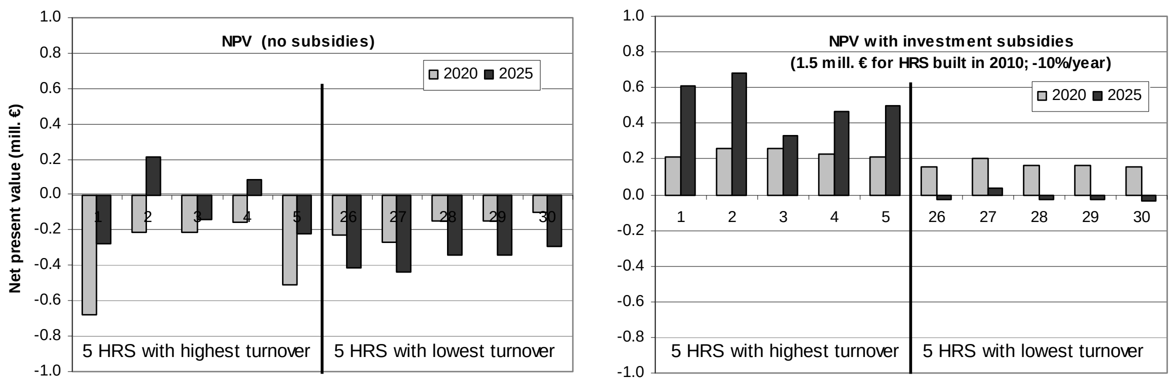

Figure 6: NPV of 5 HRS with highest and lowest turnover; w/o and w/ subsidies.

5 Conclusions

A detailed study for the hydrogen refuelling infrastructure for the Greater Oslo Area was conducted, assuming 20-30 hydrogen refuelling stations by 2025. The results suggest that over time and with increasing demand, hydrogen sources will switch from hydrogen by-product to biogas and later to electrolytic hydrogen. Hydrogen delivery is initially accomplished using vessel bundles and tube trailer trucks; later a pipeline infrastructure gradually develops to supply the most central locations. A CO_2 equivalent level of below 20 g/km is reached (well-to-wheels). A business analysis of the refuelling stations results in negative net present values by 2020 for all stations; by 2025, stations with high turnover partially achieve positive NPV. Applying subsidies, these values can be varied, but a degressive investment subsidy alone is not able to level out financial differences between stations with high and low turnover.

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