Efficient hydrogen infrastructure for bus fleets

- Evaluation of slow refueling concept for bus depots and estimates of hydrogen supply cost

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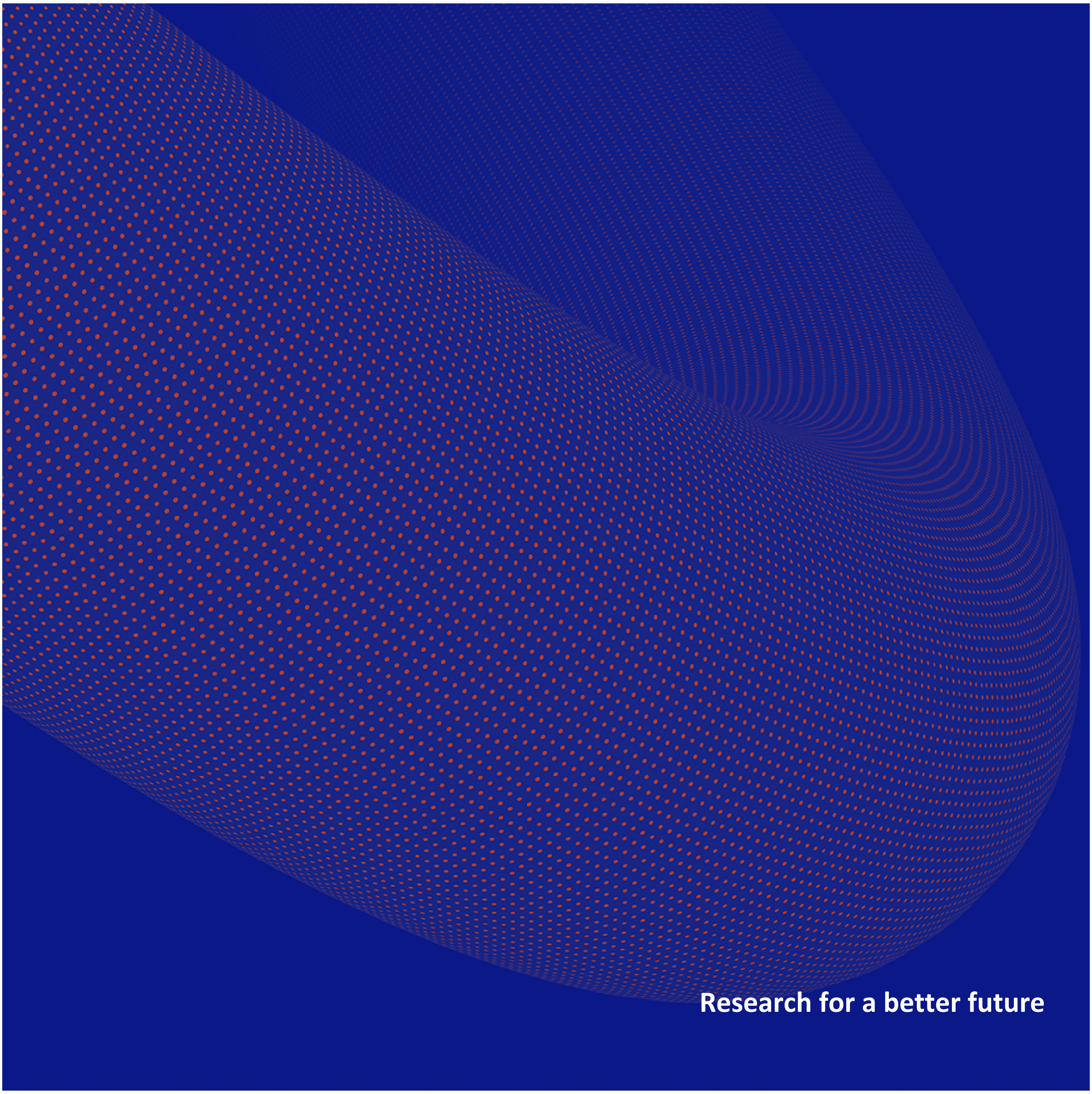
Ragnhild Hancke
Janis Danebergs
Lisa Kvalbein
Fredrik Aarskog



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Title:

Efficient hydrogen infrastructure for bus fleets – Evaluation of a slow refueling concept for bus depots and estimates of hydrogen supply cost

Summary:

Ruter AS (the public transport authority for the Oslo region) has from previous experience on fuel cell electric bus operation and procurement processes identified that fast-fill hydrogen refueling infrastructure creates challenges regarding logistics, costs, and occupation of valuable space within the bus depot.

The objective of this study has been to compare conventional methods for fast refueling of hydrogen to an alternative system using unmanned, slow filling of hydrogen in dispensers located at the parking space of each bus. The analysis is based on a case study to provide a refueling infrastructure solution for 40 high-capacity buses (24 m) running in Oslo with a daily hydrogen demand of 40 kg per bus. These buses are planned to be part of the new zero-emission bus depot at Stubberud.

Based on the timesheets of these buses and a purpose-built simulation tool, a minimum requirement for both fast- and slow fill refueling infrastructure was identified to satisfy the refueling demand for buses and identify the hydrogen demand profiles. These results are used as input to the techno-economic analyses in which the levelized cost (CAPEX and OPEX) of producing, compressing, storing, and dispensing hydrogen is compared for the fast- and slow fill configurations.

Our analyses show that the levelized costs of dispensing hydrogen is significantly higher for fast fills compared to slow fills. This is due to: i) the extra labor costs associated with a required additional driver to manage the refueling process (OPEX), and ii) the high costs of the pre-cooling machinery required to conduct fast fills (CAPEX). The former cost can easily be overlooked when making early phase estimates in such projects and underscores the importance of implementing infrastructure which is purpose-built for the transport application in question. The refueling system analysis was complemented with simple dynamic modelling of the cascade-type refueling system to verify and adjust the static calculations.

By comparing different water electrolysis-based hydrogen supply alternatives we find that on-site production with the alkaline technology is the most cost-effective option (marginally cheaper than using PEM-based systems), and that a cost of about 50 NOK per kg of hydrogen at the pump can be reached with today's technology. If hydrogen is to be supplied in transport modules from a central production facility, an additional cost of transportation of 3-11 NOK per kg of hydrogen (depending on transport distance) must be expected.

	Prepared by:	Ragnhild Hancke Janis Danebergs Lisa Kvalbein Fredrik Aarskog	(digitally signed on last page)
	Reviewed by:	Øystein Ulleberg	(digitally signed on last page)
	Approved by:	Arne Lind	(digitally signed on last page)

Institute for Energy Technology
P.O. Box 40, NO-2027 Kjeller, Norway / P.O. Box 173, NO-1751 Halden
Telephone: +47 63 80 60 00/ +47 69 21 22 00
https://ife.no / firmapost@ife.no

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1 Background & Scope of Work

Ruter AS is the administration company responsible for public transport services in Oslo and former Akershus (now part of Viken) County. They plan, commission and market public transport services. According to Ruter's ambition, all public transport services administrated by them shall run on renewable fuels by 2020 and become zero emission, including tailpipe emissions by 2028 [1]. Today, Ruter commissions approximately 1200 buses. This is expected to increase to 1500 buses by 2030 [2].

The deployment rate of battery-electric buses in Ruter's fleet has been very high the last few years – increasing from 6 battery electric buses in 2017, to 115 in 2019 – and is expected to grow in the coming years [1]. For regional transport services with relatively low frequencies, the adoption of battery electric buses will, however, not be economical due to the high costs of establishing fast chargers and insufficient range of available buses. Hydrogen- and fuel cell (FC) driven buses with a range of 300-400 km may therefore be a more suitable option for regional routes once the expected cost reductions of these technologies occur (due to mass production and economies of scale).

Through the CHIC project [3] Ruter operated 5 hydrogen-driven buses between 2012-2016. The hydrogen refueling station (HRS) was in this case equipped with commercial fast fill dispensers (refueling time of 10-20 minutes), which are typically adopted for public access fuelling stations. Ruter experienced that this technology was not ideal for their needs because a queue formed every time multiple buses arrived the station simultaneously. Consequently, the driver's allocated working time was exceeded. This was solved by manning the station with an extra driver, inflicting significant additional costs to the bus operation [4].

If Ruter is to upscale today's solution, the issues related to queuing will be amplified as most buses arrive the depot around the same time during the evening. This can be alleviated by over-dimensioning the HRS with additional refueling points, and/or by staffing up to be able to rotate the buses overnight. Both increasing the number of dispensers and/or staffing up will result in a steep increase in refueling costs and reduce the anticipated benefit of economies of scale for a larger bus fleet.

In this study it is hypothesized that a refueling system based on unattended slow fills taking place overnight would be a preferable solution over the fast fill solution due to:

- Reduced personnel costs
- Less space requirements because the buses are refuelled where they are parked
- Cheaper refueling infrastructure

The objective with the work in this study was to evaluate concept design for a hydrogen refueling system based on unattended slow fills of 40 buses at a bus depot and assesses the resulting fuel costs. These are compared to the costs of conducting fast fills at the same scale with a person dedicated to move buses to and from the fast fill dispenser(s). The zero-emission bus depot under planning at Stubberud in Oslo is used as a case study for the analyses, and the running schedule of Ruter's bus lines 20 and 21, consisting of 40 high-capacity buses (24 m), serves as a basis for the analysis. These bus lines have previously been identified by Ruter as good candidates for hydrogen driven fuel cell buses and they have ongoing activities to prepare the necessary knowledge base.

Based on estimated energy demand and a timetable of the currently operating busses, a demand profile and the minimum number of dispensers is identified for both fast and slow fill system solutions. From these requirements a techno-economic model is built to provide Ruter with a knowledge base of the expected near-term costs and technical parameters of hydrogen refueling system including both fast and slow fill systems.

2 Design of Hydrogen Refueling Station

Both the fast and slow hydrogen refueling system (HRS) designs analyzed in this work are based on cascade-type overflow refueling from buffer storages containing pressurized gaseous hydrogen. In these types of systems, the empty onboard tanks of the buses are refueled by natural overflow induced by the pressure difference between the receiving storage tanks and the releasing storage tanks.

The proposed dispensing system for slow fill is shown in Figure 1. This system concept is designed for unattended overnight fills, implying there should be one refueling hose available at each parking space. These hoses will only need simple on/off valves and a nozzle with a retractor. Each set of filling posts ([A…Z] in Figure 1) are served by one of the main refueling branches [1…n] equipped with a flow controller ensuring the maximum fueling rate of 1.8 kg/min is never exceeded [5]. At this refueling rate communication between the vehicle and refueling station is not required, and a simpler and less expensive connector can be used. It also eliminates the need for pre-cooling of the hydrogen being dispensed to the bus.

The envisioned filling protocol is the following: The flow controllers are operated in parallel and sequentially cycle through each of the occupied parking spaces (connected hoses). When the bus(es) have been refueled by the low pressure (LP) storage via Line 1 (i.e. when the flow of hydrogen starts to slow due to a decreasing pressure difference), the same procedure is repeated with Line 2 from the high pressure (HP) storage to complete the fills. With this configuration, the maximum number of buses being refueled simultaneously always equate to the number of flow controllers.

The refueling workflow for a slow fill will be the following (modified from [6]):

1. Bus arrives at depot
2. Bus is inspected and outside cleaning is done if necessary
3. Bus parks at parking space
4. Driver connects the refueling hose
5. Bus is cleaned inside while parked, and refueled unattended overnight
6. Driver disconnects the refueling hose in the morning

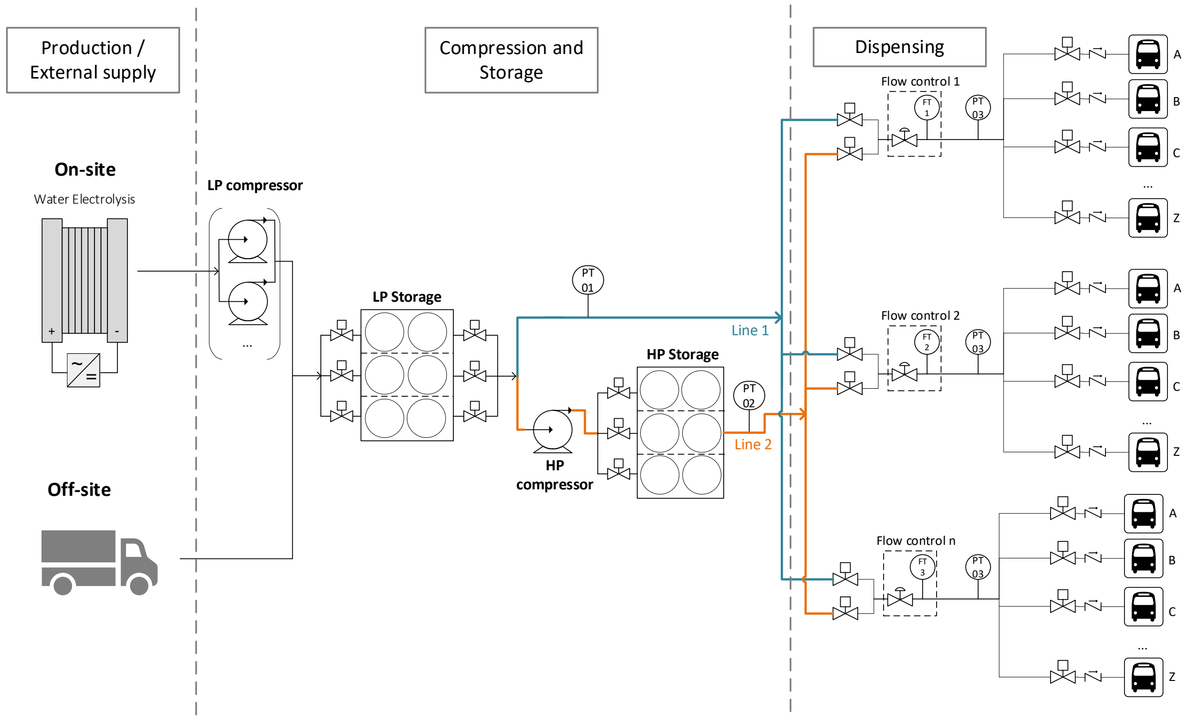

Figure 1: Layout of proposed HRS and refueling configuration for slow filling of hydrogen

In the case of fast filling we assume that standard commercial hydrogen dispenser cabinets (with two hoses) capable of refueling the bus in about 15 minutes are installed. Fast filling demands active communication between the vehicle and the refueling station, typically via an infrared link in the connector. This, the internal, sophisticated metering device, and the precooling unit[1] make these types of hydrogen dispensers significantly more expensive and energy demanding than the slow fill system described above, and one can therefore not dedicate an individual hose to each bus. The fueling workflow for a fast fill will therefore necessarily be different from slow fills:

1. Bus arrives at depot
2. Bus is inspected and outside cleaning is done if necessary
3. Bus is parked in que to wait for available dispenser (if there is a que)
4. A hydrogen fuel operator (an individual dedicated to servicing the bus), moves bus to refueling island and begins refueling
5. Bus is cleaned inside while refueling
6. When filling is completed, the H2-fuel operator disconnects the dispenser
7. the H2-fuel operator moves bus from refueling island to its parking space (the H2-fuel operator repeats from step 4 with next bus)

Washing of the buses' exterior at the depot is only carried out when necessary, and thus a random time step between 0 and 15 minutes is added to the effective fueling time in the simulation of both slow and fast fills in order to account for irregular washes. For the fast fills, an additional lingering time of 5 minutes is added to each bus to account for the extra time needed to disconnect the bus, move it from the refueling island, and move and connect the next bus.

The effective refueling rate is assumed to be 0.8 kg/min in the case of slow fills, and 1.7 kg/min for fast fills. These rates are considerably lower than the accepted maximum rates [5], but represents the nature of the SAE J2601 refueling standard. This standard is based on a linear pressure increase in the onboard tank during the refueling event, and due to the non-linear correlation between volume and pressure of gases, the highest speed will be obtained only in the beginning of the refueling period. In addition, standard procedures such as start-up time, leak check, cascade bank switch, etc. will further decrease the average experienced refueling rate [7].

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[1] Ensuring H_2 is cooled to - 40°C before entering the vehicle's tank to allow fast fuelling up to 3.6 kg/min without overheating the tank

3 Methodology

The assessment of the bus depot HRS design and costs focused on several subsystems and processes, namely the hydrogen demand, the dispenser, compression, storage system, and production/supply systems. The workflow is illustrated in Figure 2: Several of the steps are interdependent, and dynamic analyses are included when feasible.

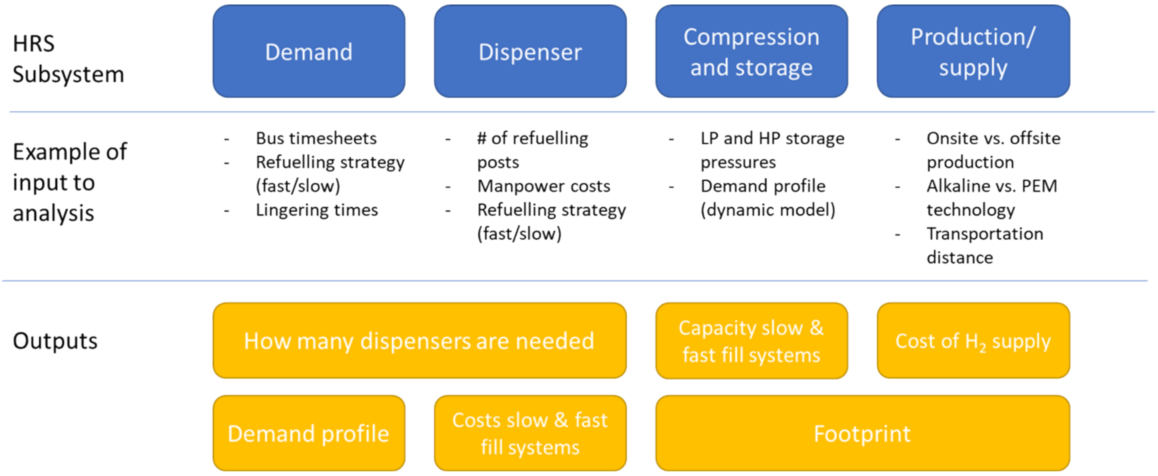

Figure 2: Overview of HRS system and processes reviewed in this work and the main outputs.

3.1 Modeling of Hydrogen Demand

To simulate logistics at the depot when refueling with various designs of HRS and to obtain hydrogen demand profiles, the SimPy [8] package from Python was used. SimPy is a framework for discrete event simulations, including the possibility to model shared resources with limited capacity and processes. A process for the arrival of buses at the depot, used for sensitivity of leap time before the bus starts to refuel, and a process of the fueling is modelled. In this model the arrived bus “asks” for a refueling post. If there are any posts available, the refueling starts right away, otherwise the bus will be placed in a queue and the refueling will automatically start later. The number of access points is an input parameter to the model, together with the time sheet of arrival of buses received by Ruter and the filling strategy (slow/fast). To check whether the number of refueling posts meet the fueling need, the total number of buses at the depot and the number of buses not refueled is compared. Once the total number of buses at the depot is always greater than the number of buses not refueled, the required number of refueling points is found, and the corresponding hydrogen demand profile is calculated.

3.2 Modelling of HRS

The simulation tool utilized for techno-economic analyses is developed in the program Engineering Equation Solver (EES) and can be adjusted and used to access the techno-economics of hydrogen production (water electrolysis), compression, storage and dispensing systems. The main technical performance parameters (e.g. efficiency, lifetime, auxiliary power needs) and cost functions for the main systems and key pieces of equipment (e.g. specific costs as a function of rated power or flow rates) are provided in Figure A-1 and Figure A-2 in Appendix A. The economic parameters (e.g. electricity price, interest rate, project lifetime) are also included in Appendix A. From this, the model calculates the total CAPEX and OPEX, and eventually the levelized cost of hydrogen (LCOH) for different operating scenarios based on

$$LCOH = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + E_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}} \tag{1}$$

where; I_t is the initial investment in year t, M_t are the operations and maintenance costs, E_t are the fuel costs, H_t is the hydrogen produced in the year t, r is the discount rate, and n defines the system lifetime [9].

The techno-economic models employed in this study are based on up-to-date technical performance data obtained from leading water electrolyzer companies and other hydrogen technology suppliers around the world, as well as cost data collected in various projects conducted at IFE over the past few years. Based on the cost data and a set of technical and economic assumptions, our model calculates the full levelized delivery cost of hydrogen including CAPEX and OPEX for the hydrogen production and supply system.

4 Results and Discussions

In this chapter the results of dynamic simulations of buses at the depot, the component sizing, and the cost breakdowns are presented and discussed. Cost data for key components and the basic economic assumptions are provided in Appendix A.

4.1 Hydrogen demand and sizing of dispenser system

Based on the timesheet for bus lines 20 and 21, the number of buses at the depot per minute was calculated. As the timesheet is repeated every week, only one week was calculated. Figure 3 shows that only 3 buses are left in the depot during rush hour Monday-Friday, while all buses are parked for two hours night-time on weekdays. In general, many buses tend to arrive at the same time, clustered around 18:00, 21:00 and 01:00. During the weekend, the routes have a lower frequency in peak hours and are served throughout the night, with the consequence that fewer buses arrive at the depot simultaneously.

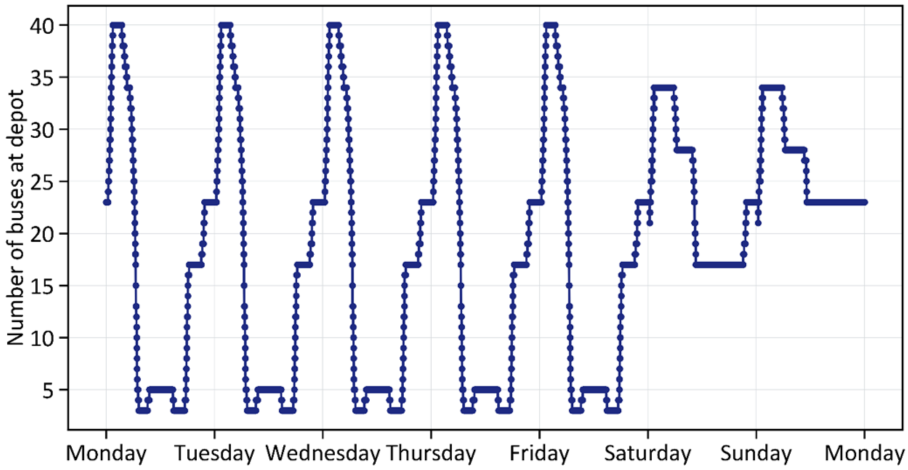

Figure 3: Number of buses at depot during a week.

For the filling strategies, three sensitivities regarding washing of the buses' exterior before refueling was carried out: 0 minutes, 15 minutes, and random for each bus between 0 and 15 minutes. The sensitivity was tested for both slow fill and fast fill. It is furthermore assumed that all buses are filled with 40 kg hydrogen, even though the actual need might vary.

4.1.1 Slow fill

All simulations of the slow fill were performed with 2 and 3 flow controllers. For all the sensitivities, the result was the same: with 2 flow controllers, the fueling need was not met due to lack of available buses during a few minutes in the morning on working days. Hence, 3 flow controllers (i.e. 3 parallel refueling events) are required to refuel all buses on time. Figure 4 provides a visualization of these findings as it compares the number of buses in the depot with the number of buses which have not yet been refueled (the results were obtained with a random outside washing time, but the other alternatives (0 and 15 min) returned similar results). The few buses which have not finished refueling before they are required to start their operation when only 2 flow controllers are available are seen in the morning at 7:15. With one additional flow controller much larger flexibility is gained. The final hydrogen fueling profile for the same day with 3 flow controllers is seen in Figure 5.

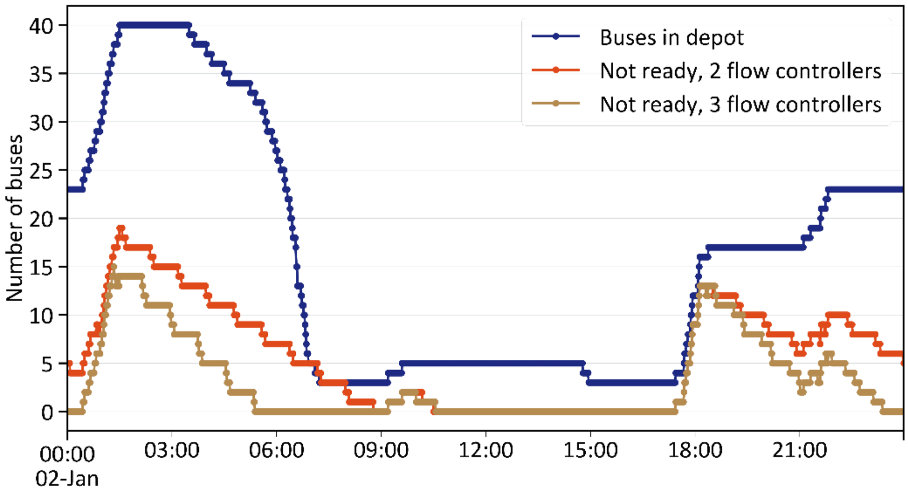

Figure 4: Total number of buses in depot and the number of buses not ready to drive routes on a workday with slow fill.

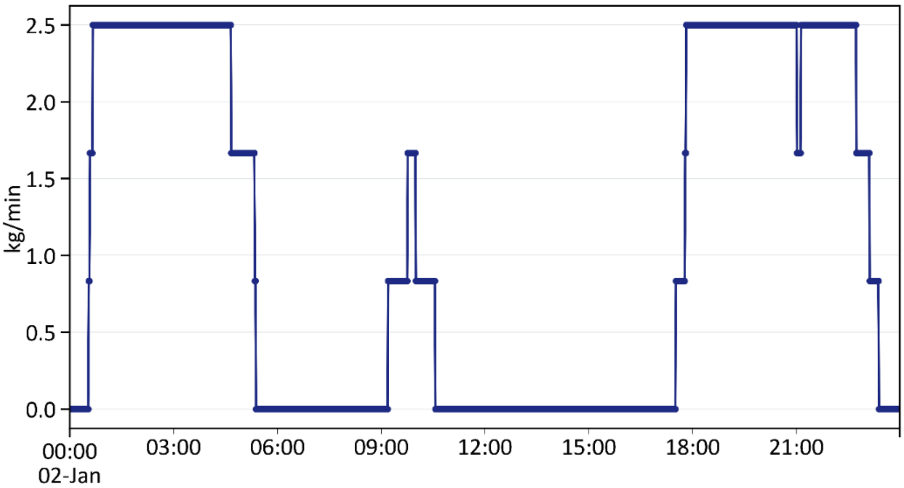

Figure 5: Hydrogen demand profile for slow fill with 3 flow controllers on a workday with slow fill

4.1.2 Fast fill

All simulations of the fast fill were performed with 1 and 2 refueling hoses. Also, here the sensitivities gave the same result: 1 refueling hose is not enough and 2 is the smallest number of hoses needed to meet the demand. With 2 refueling hoses also for fast-fill system a much larger flexibility is gained. Visualization of the comparison between one and two hoses and hydrogen demand profile is shown in Figure 6 and Figure 7 respectively. In Figure 6, at any time when the number of buses not ready is greater than two there is a que, and an extra person (the H2 fuel operator) is needed for rotating the buses. The fluctuations in demand seen in Figure 7 is due to the lingering time of 5 minutes between each refueling event.

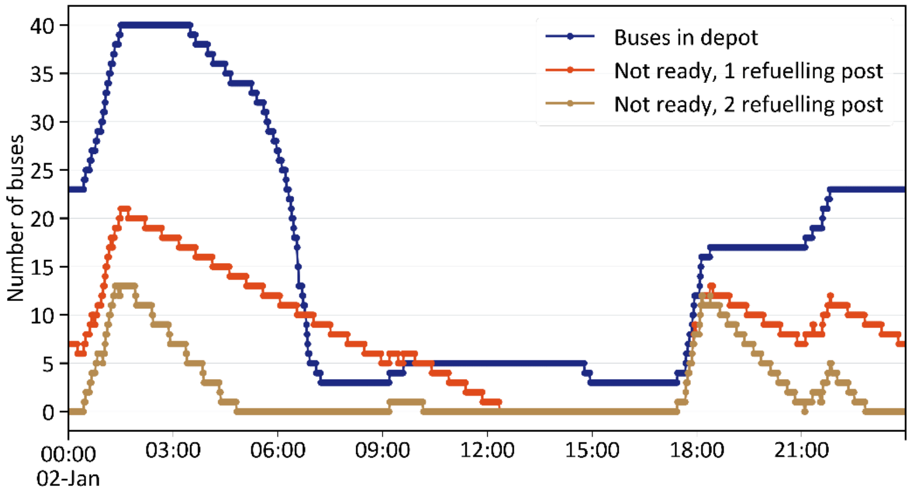

Figure 6: Total number of buses in depot and the number of buses not ready to drive routes on a workday with fast fill.

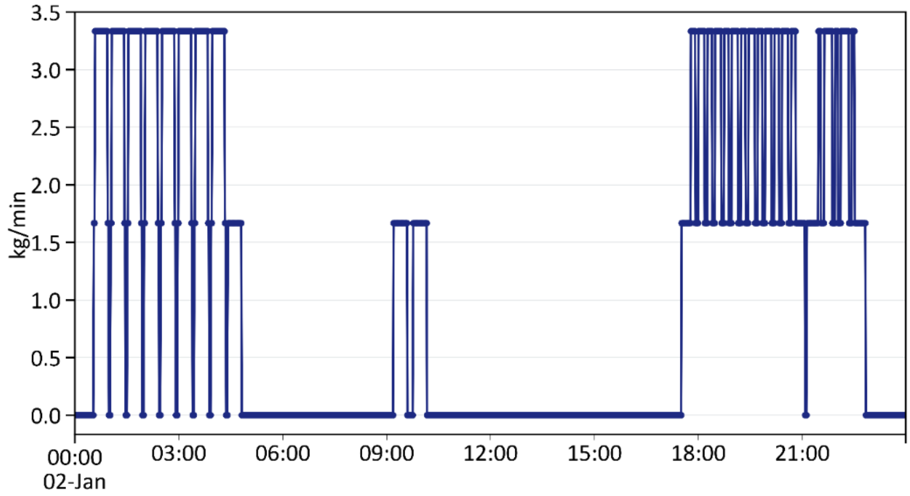

Figure 7: Hydrogen demand profile for fast fill with 2 refueling hoses on a workday.

Fueling activities with fast fill is happening in three time slots: 00:29-04:48 (4,5 hours), 09:12-10:09 (1 hour) and 17:31-22:49 (4,5 hours). For the middle time slot after the morning rush hour it is assumed that the bus drivers can move the buses themselves without exceeding their driving- and rest time. For the two other refueling periods an additional H2 fuel operator is needed. On weekends fewer busses arrives the depot simultaneously and only after midnight a queue is created between 00:29-04:48 (4,5 hours).

4.2 Dispensing system

Based on the simulations above, the costs of carrying out slow fills at the depot can be compared to fast fills. For commercial 350 bar fast fill dispensers, a cost of 0,9 MNOK per dispenser and an additional cost of about 10 MNOK for the cooling system has been assumed (the latter depends on peak H_2 demand and thus installed nominal cooling capacity) [10]. Since the hydrogen dispenser cabinets are equipped with two hoses – the minimum required number to serve the 40 buses at Stubberud (Figure 6) – it will be sufficient to install one dispenser at the depot.

For slow refueling systems, cost data is not available from commercial suppliers. We have therefore estimated the CAPEX of this system based on the configuration shown in Figure 1 and known costs for the various high-pressure, EX-proof components (flowmeters, pressure transmitters, pressure control valves, tubing, etc.). This adds up to a total CAPEX of about 1 MNOK for the slow fill dispensing system, which consists of 3 flow controllers (Figure 4) and 40 dispenser hoses (each equipped with a nozzle, a non-return valve and an on/off valve with an actuator).

Figure 8 shows the calculated levelized cost of hydrogen (LCOH) for the different hydrogen dispensing solutions, assuming that 1600 kg H_2 is dispensed at the bus depot every day. Notice that this is the cost of the dispensing system only, and does not include hydrogen production, compression, and storage. The cost item “fixed assets” accounts for installation costs, site preparation and engineering, and is assumed to correspond to a certain fraction of the CAPEX, just as the operation and maintenance costs (see Appendix A). The costs of the cooling system and its electricity consumption is calculated based on the demand profile shown in Figure 7, while the electricity consumption of the dispensers themselves is assumed negligible. To account for the extra labor costs associated with fast fueling, we have made a conservative assumption that one 8-hour driver’s shift (400 NOK/hour) will cover the demand. In practice, two such daily shifts may be required to serve the buses during the periods with high demands (between 00:29-04:48 and 17:31-22:49) during working days, with only one nightshift in weekends. The shaded area in the bar chart indicates the added cost in this case.

These results show that the cost of fast refueling with the proposed system will be about 5 NOK/kg (including 2 NOK/kg for the extra manpower) whereas slow refueling will cost less than 1 NOK/kg. It has been suggested [11] that for vehicles equipped with Type III onboard storage tanks (having a metal liner), pre-cooling of the gas is not required to carry out fast fills. In this case, the cooling machinery and its energy consumption can be avoided, and it will be possible to carry out fast refueling significantly more cost efficiently (the *fixed assets* and *O&M* expense items will also be reduced).

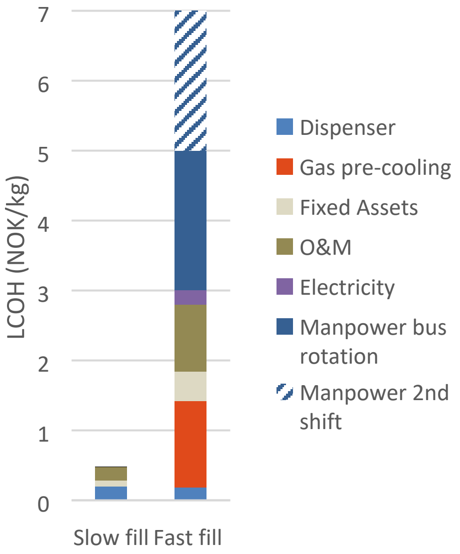

Figure 8: Levelized cost of hydrogen (LCOH) for the dispenser system: slow and fast refueling configurations compared.

4.3 Hydrogen Compression and Storage System

For the dimensioning of the hydrogen compressor and storage, we have carried out static and dynamic system modelling of the HRS and performed sensitivity analyses with respect to hydrogen compressor- and storage capacities and LP storage bank pressure to determine the most cost-effective configurations. The static analysis has been made in form of a sensitivity analysis, shown in detail in

Appendix B and the dynamic analyses as a separate part in Appendix C. The costs and specifications of Hexagon's X-Store gas modules (type IV storage tanks) at 250, 300 and 500 bar storage pressure, as well as the compressor costs presented in Appendix A, are used in these analyses.

With a slow-fill system the most cost-effective design is when the LP storage bank is designed to include pressure vessels at 300 bar, and the "equilibrium" pressure (*i.e.* the pressure at which refueling shifts from line 1 to line 2 in Figure 1) is 200 bar. On this basis, it is found that a minimum of about 2 tonnes of hydrogen must be installed in the LP hydrogen storage bank to be able to carry out natural overflow-based refueling of the buses (there will always be a significant difference between installed and useable hydrogen capacity in cascade-based hydrogen refueling systems). Furthermore, the footprint of this LP hydrogen storage bank will be about 90 m^2 [12].

For the HP hydrogen storage (500 bar), the static modelling suggests over 2.8 tonnes of hydrogen storage capacity must be installed to complete filling of the 40 buses' onboard tanks from 200 to 350 bar. However, we have also carried out dynamic simulations assuming that the HP hydrogen cascade system is sectioned into 3 modules. The replenishment rate of these modules is modelled as a function of the pressure level in HP hydrogen tank while the LP hydrogen tank level is assumed constant at 200 bar. A more detailed description of the method can be found in Appendix C.

The results for dynamic operation of a slow fill system during three subsequent days is shown in Figure 9, including variation in pressure and flow in and out from all three storage tanks. The result from the modelling shows that the smallest feasible compressor size is 8 kW and the total required HP hydrogen storage capacity is 825 kg$_{H2}$ including the "dead" weight of hydrogen to maintain the required pressure. In comparison, if fast refueling dispensers would be deployed the minimum compressor and HP hydrogen storage size would increase to 9 kW and 900 kg$_{H2}$, respectively. This shows that a fast fill hydrogen system would increase both the costs and physical footprint of the HP hydrogen compressor and storage slightly.

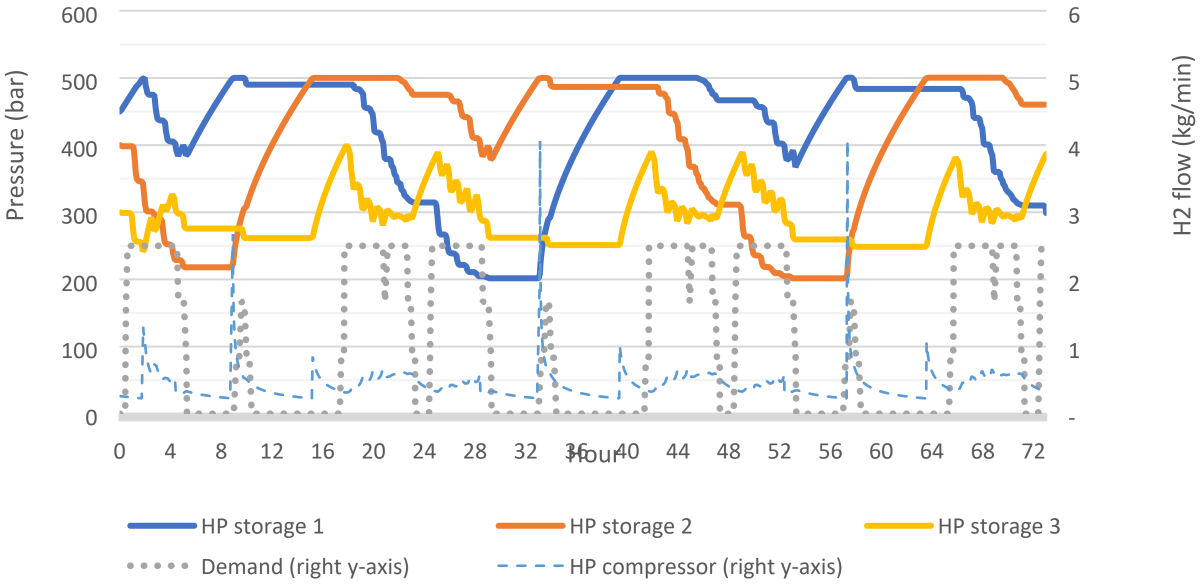

Figure 9 Example of a three-day operation of the HP hydrogen storage and compressor in the slow filling concept.

4.4 Hydrogen production or supply system

The two commercially available options for water electrolysis (WE) are atmospheric alkaline systems and the pressurized technology based on polymer electrolyte membranes (PEM). Each have their advantages, but the major drawback of the PEM-technology is that it is significantly more expensive than alkaline systems. The specific investment costs of the two technologies are reviewed in detail in Appendix A. Based on this, we have assumed a specific investment cost of 860 EUR/kW_{input} for an alkaline system and 1350 EUR/kW_{input} for a PEM-based system, each producing 1600 kg/day. Assuming a system efficiency of 55 % (corresponding to 60 kWh/kg_{H2}), an installed capacity of approximately 4 MW (or 2x2 MW modules) will be required, and the installation will have a footprint of about 400 m^2 in case of an alkaline system, and 200 m^2 for the PEM-based system [12].

Figure 10 shows the levelized cost of producing and compressing hydrogen to 300 bar (i.e. to match the LP storage tank) in a system based on the alkaline and PEM technology, respectively. Interestingly, it can be seen that alkaline systems (output pressure 5 bar) is only marginally more cost-efficient than PEM-based systems (output pressure 30 bar) because the cost difference in favor of the alkaline electrolyzers is almost offset by the high costs associated with mechanical hydrogen compression when the suction pressure is only 5 bar. For an alkaline production system, one would need to install a total compressor capacity of 261 kW, whereas only 110 kW is needed with a PEM-based system.

It should also be recognized that electricity makes up more than 50 % of the overall hydrogen costs (assuming 0.36 NOK/kWh). This highlights the importance of pursuing higher efficiencies of large scale WE systems.

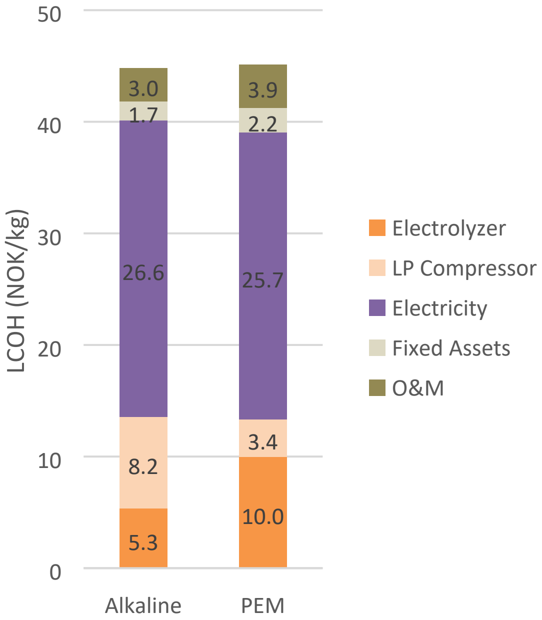

Figure 10: Levelized cost of hydrogen produced by water electrolysis and mechanical compression and supplied at 300 bar; calculations based on alkaline and PEM technologies with delivery pressures of 5 and 30 bar, respectively..

Since available space will be very limited at the depot, it is possible that the HRS will be based on gas deliveries from a central production plant instead of onsite production. By way of example, the joint venture Green H2 Norway AS has the intention to develop a centralized production plant nearby Oslo with its main aim to supply hydrogen to fuel cell electric trucks [13]. The main benefits with centralized large-scale production of hydrogen is the the economy of scale and flexibility with respect to the location of the hydrogen production plant. If located correctly, an electrolyzer can take advantage of a more efficient/cheaper grid connection and/or sales of its by-products such as oxygen and heat. The main disadvantage is the additional cost to transport the hydrogen to end-user.

In Appendix B a comparison has been made for transportation of hydrogen by truck with hydrogen transport modules at either 300 or 500 bar pressure. A sensitivity analysis has been carried out with variables such as the transportation distance, the size of the transport module, and lifetime of the storage. When the transportation distance is less than 200 km, the most feasible option is 300 bar gas cylinders in a 40-foot container (despite the higher payload achieved when transporting the gas at 500 bar). Each such gas module placed in 40 feet containers carries 835 kg_{H2}, and up to three daily deliveries would therefore be required to cover the daily demand at the bus depot. The transport costs vary mainly with the distance, and for a distance range between 10 to 200 km, the costs vary between 3-11 NOK/kg_{H2}.

4.5 Summary of HRS system design and costs

A summary of the HRS system design considered in this study, including the rated capacities and footprints of the key components and systems in the hydrogen supply chain is provided in Figure 11.

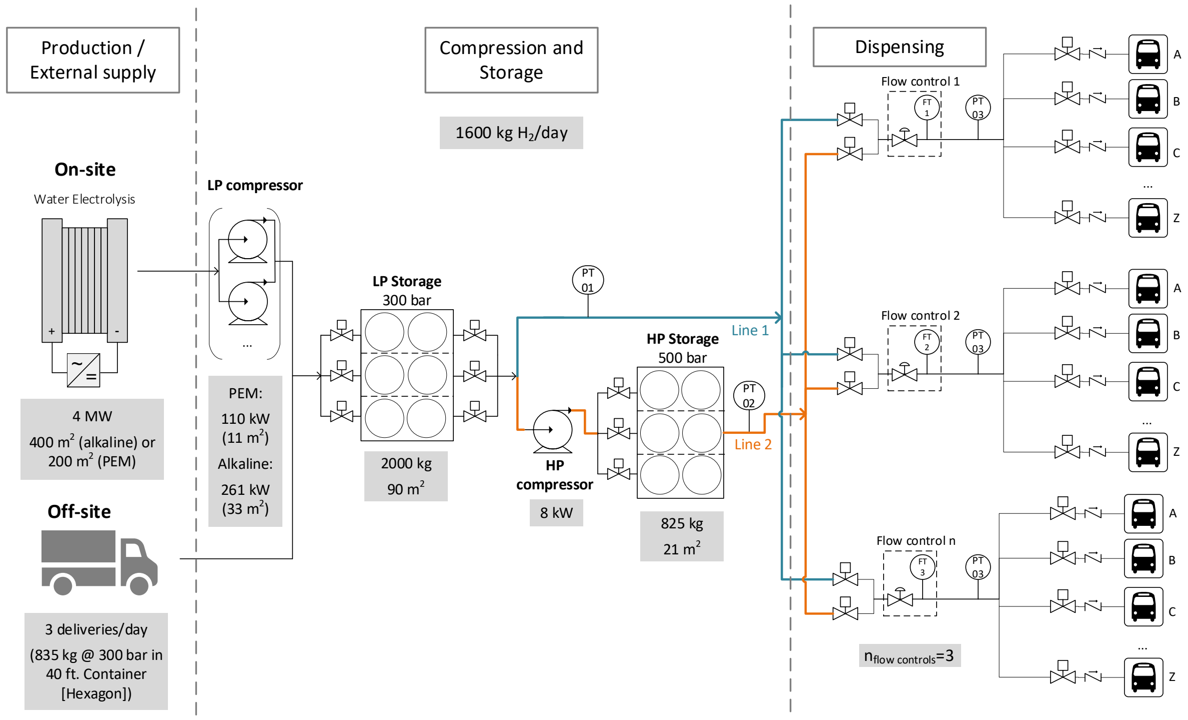

Figure 11: The rated capacity and footprint of the key components and system in the hydrogen supply chain for the optimized hydrogen refueling system designs. (Footprints for components derived from [12] and [14]).

With *local* production of hydrogen, the total, levelized cost of producing, compressing, storing, and dispensing 1 kg of hydrogen at the bus depot with a daily turnover of 1600 kg will amount to about 50 NOK/kg_{H2} with today's technology costs (the alkaline technology is marginally more favorable than PEM-based systems). This is a massive cost reduction compared to 130-150 NOK/kg_{H2} which were the costs for refueling of the 5 buses in the CHIC demonstration project [2].

Assuming that the HRS is supplied from a large-scale external alkaline production plant with a capacity of 5000 kg/day, we see a small effect of economies of scale by increasing the compressor and electrolyzer capacities from 1600 kg/day, but the added transportation cost makes this is an overall less economic option for the bus depot.

It should be noted that Nel has announced [15] that with the ongoing expansion and optimization of their alkaline electrolyzer manufacturing capabilities, together with improvements of the electrolyzer designs, they are targeting a >40% cost reduction. They anticipate they will be able to sell large-scale alkaline systems for about 400 USD/kW$_{input}$ with an energy consumption of about 50 kWh/kg$_{H2}$. In this case the LCOH will approach 45 NOK/kg$_{H2}$ (assuming no change in compressor cost or efficiency).

In Figure 12 these findings are summarized, where the overall dispensing costs of hydrogen is compared for local production with today's costs (PEM and alkaline technologies), off-site production (transport distance 100 km), and the alkaline electrolyzer cost- and efficiency targeted by Nel.

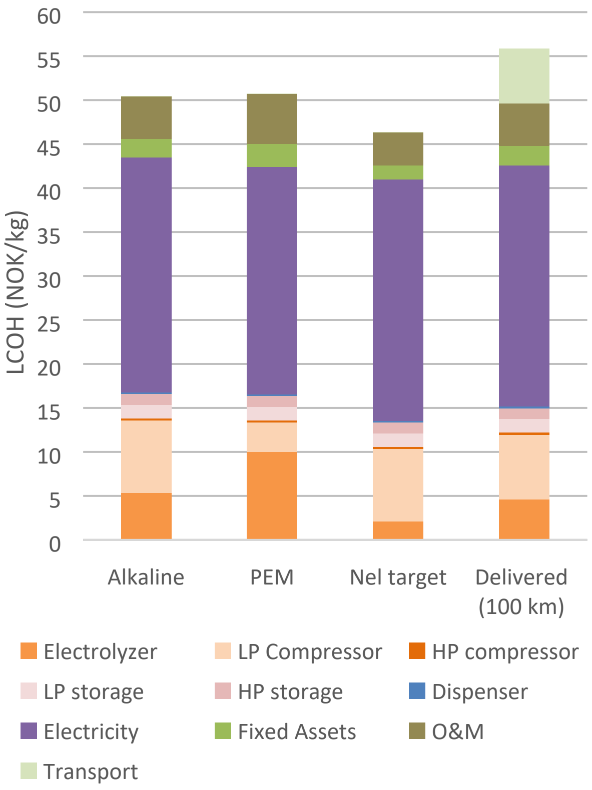

Figure 12: Total levelized cost of hydrogen (LCOH) for producing, compressing, storing and dispensing 1 kg H_2 compared for local production with alkaline and PEM technologies, off-site production at large scale production facility (5000 kg/day, alkaline technology), and the alkaline electrolyzer cost target stated by Nel Hydrogen (400 USD/kW$_{input}$).

The refueling system based on slow fills has a great possibility to reduce the area demand as buses will be refueled at the same location as they are parked. However, further investigation needs to be made regarding the safety aspects and possible safety zones which might alter the outcome. It has also been found that in the case of fast fill systems only one dispenser with two hoses would be required to refuel the buses on time. This is a decrease by two dispensers comparing to Ruter's preliminary draft solution and could therefore provide space savings in a scenario for fast fill system (albeit dispenser redundancy should probably be implemented).

In this preliminary analysis a constant electricity price and fixed grid fee depending on kW of installed capacity was assumed. Considering the large effect of the production costs coming from electricity price it is relevant in future studies to look closer at the future development of electricity prices and how the risk of exposure to variable electricity prices can be reduced. Also, grid fees, which are strongly connected to the peak (hourly) demand of the entire bus depot, should be more closely investigated. The grid fee could to some extent be reduced if the electrolyzer is operated in a flexible manner and is ramped down when peaks of other loads are occurring (i.e. fast-charging of buses). It may also be explored if the flexibility of the electrolyzer can be offered as a service to the grid owner, in terms of offering to reduce power consumption in hours of high demand.

5 Conclusions and Outlook

In this study various aspects of how fast and slow fill HRS systems at a bus depot will affect the fueling costs has been evaluated and analyzed in detail. The main cost savings related to the implementation of a slow hydrogen refueling concept is of the reduction of cost related to personnel (OPEX) and pre-cooling system (CAPEX), amounting to a total savings of approximately 4.5 NOK/kg$_{H2}$.

Another important issue is that, fast filling logistics require extra hours for the drivers, due to waiting time for refueling. This extra personal cost (OPEX) has been calculated to be about 2 NOK/kg$_{H2}$, which is a significant hidden cost that should be taken into account when evaluating different zero emission solutions for bus fleets. The same challenge may also be present for other type of fleets with a dedicated depot, including trucks with logistic centrals, and taxi fleets.

The dynamic modelling performed in this study shows that by implementing slow hydrogen refueling systems, both the hydrogen compressor and storage can be downsized compared to fast hydrogen refueling systems, and that additional savings thus can be achieved. In summary, it can be concluded that significant cost savings can be achieved by implementing slow-fill solutions for a fleet of hydrogen and fuel cell driven buses.

By comparing different water electrolysis-based hydrogen supply alternatives we found that on-site production with the alkaline technology is the most cost-effective option (marginally cheaper than using PEM-based systems), and that a cost of about 50 NOK/kg$_{H2}$ at the hydrogen dispenser can be reached with today's technology. This is a significant cost reduction compared to the 130-150 NOK/kg$_{H2}$ which were the hydrogen refueling cost experienced by Ruter in their previous demonstration project with 5 buses. However, our calculations do not include the cost of land area, which probably would favor the more compact PEM water electrolyzer systems (ca. 200 m^2) instead of the alkaline technology (ca. 400 m^2).

If hydrogen is to be supplied in transport modules from a centralized production facility, an additional cost of transportation of about 3-11 NOK/kg$_{H2}$ must be expected, depending on transport distance of 10 to 200 km at the cheapest transportation pressure of 300 bar. Nonetheless, this solution may be the preferred option due to the space limitations at the Stubberud property (a 4 MW PEM-based H_2 generation system would require about 200 m^2, excluding safety distances).

This work in this study provide insight into many aspects related to the dimensioning and costs of an HRS system based on slow fueling of hydrogen. However, to realize the potential of efficient hydrogen refueling at bus (or truck) depots, further studies should be carried out. We recommend the following topics for further research and analysis:

- A preliminary detailed design of a slow fill system should be made based on the concept provided in this study. A risk analysis can then be made, in addition to a more detailed evaluation of the required area including safety distances.
    - Slow filling speeds might simplify the system further as smaller pipe dimensions can be used. Furthermore, the overpressure in the HP hydrogen storage may be reduced. These changes may reduce both the component costs and required safety distances.
- It would also be interesting to evaluate whether slow fill solutions are feasible in other types of vehicle depots with different logistics and different hydrogen demand profiles. One example could be a logistic center with hydrogen powered trucks.
- An analysis of the entire local energy system at the depot, including other loads such as charging of battery-electric buses and the local grid constraints, should be made. Such an

analysis could identify both conflicts related to available grid access and advantages in utilizing the grid access in a more efficient manner.

- This work in this study highlighted the high costs related to mechanical compression of hydrogen from the electrolyzer outlet to LP storage pressure. These costs are based on earlier experience from IFE of high maintenance demand of hydrogen compressors. A more precise examination of the hydrogen compressor reliability is of high relevance to be able to confirm the current assumptions of the compressor maintenance needs in IFE's techno-economic model.

6 Acknowledgements

We would like to thank Ruter and especially Pedram Nadim for giving us the opportunity to investigate this novel depot-based hydrogen refueling solution and for providing valuable input about how the bus depot is operating. In addition, would like to thank the Regional Research Fund "Hovedstaden"[2] for providing the economical means to execute this pre-project (project number 310551).

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[2] https://www.regionaleforskningsfond.no/hovedstaden/

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Appendix A - **Cost data and Economic Assumptions**

The figures below show the specific capital costs of water electrolyzers and hydrogen compressors, respectively, as a function of capacity. The compressor data, based on quotations from suppliers, were collected in connection with Task 33 of IEA's Hydrogen Technology Program and first presented at ICE 2017. The figures highlight the importance of economies of scales by moving from small to medium capacities, and hence the intrinsic cost-inefficiency of small-scale systems such as those studied herein.

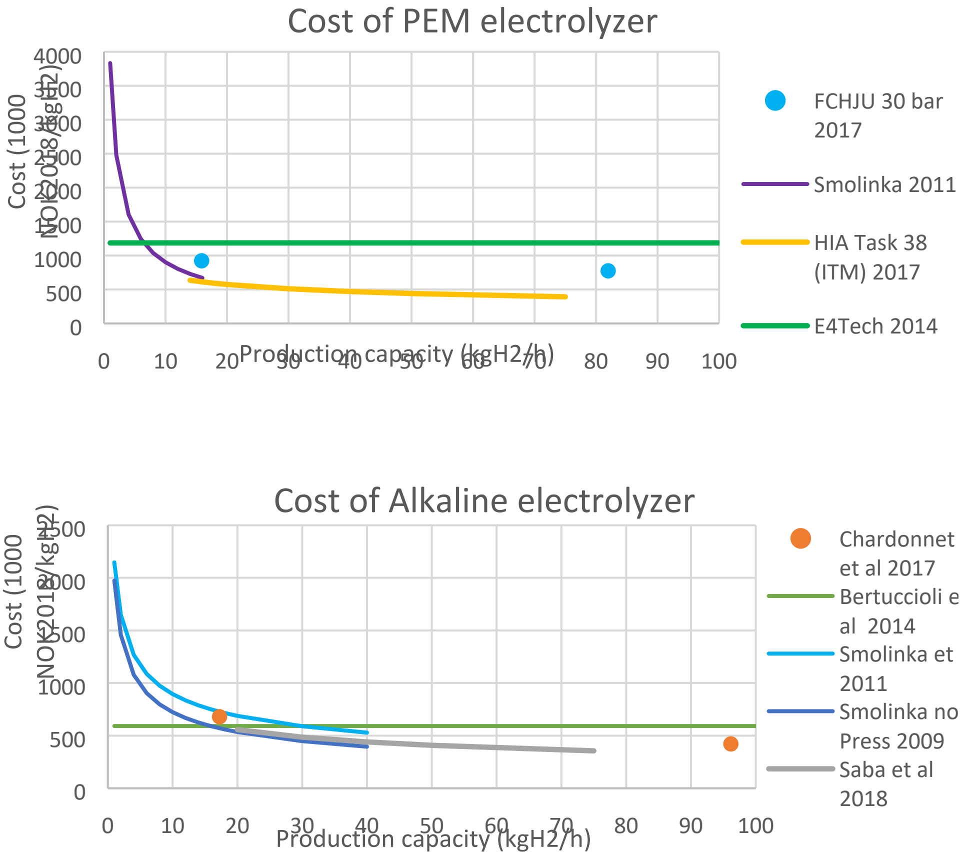

Figure A-1 Specific capital costs of PEM and alkaline water electrolyzer systems (Bertuccioli et al., 2014; Chardonnet et al., 2017; Proost, Saba, Müller, Robinius, & Stolten, 2018; Smolinka, Günther, & Garche, 2011; Ulleberg, 2019; Saba, Müller, Robinius, & Stolten, 2018; Smolinka et al., 2011).

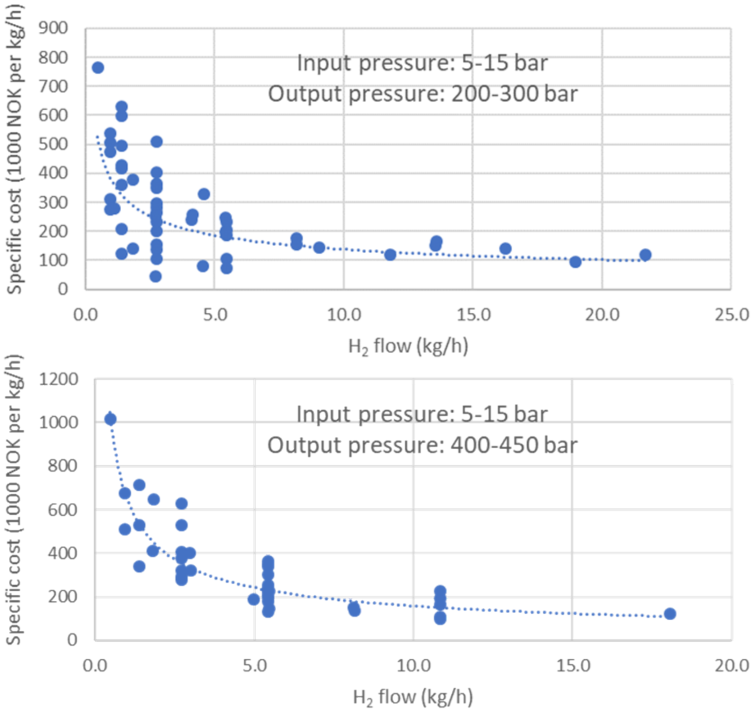

Figure A-2: Specific capital costs of compressors for various input and output pressures [1].

The general economic assumptions made in the system simulations are summarized in Table A-1. The site preparation, engineering and installation costs are also referred to as *fixed assets*.

Table A-1 Economic assumptions made in the system simulations.

Lifetime plant (years)	30
Lifetime dispenser (years)	10
Lifetime compressor (years)*	10
Lifetime storage (years)	30
Lifetime alkaline/PEM electrolyzer (years)	10/7
Interest rate	4 %
Site preparation costs (of CAPEX)	5 %
Engineering costs (of CAPEX)	10 %
Installation costs (of CAPEX)	10 %
Operation & Maintenance costs (of CAPEX)	3 %
Contingency	5 %
Electricity costs (NOK/kWh)	0.36
Power costs (NOK/kW)	481
Fixed Grid costs (NOK/year)	12900

*Full compressor overhauling after 10 000 h of operation. Overhauling costs is 20 % of compressor CAPEX

1. Ulleberg, Ø., *Hydrogen Implementing Agreement - Task 33*. n.d., IEA Hydrogen.

Appendix B - **Sensitivity analyses**

In the following, the dimensioning of the HP compressor and the LP and HP storage is discussed and optimized.

In a cascade type refueling system, the cascade bank should have at least 100 bar higher pressure than the receiving tank[1], and the HP storage bank is therefore assumed to contain gaseous H_2 at 500 bar. The choice of LP storage bank pressure (either 250 or 300 bar), as well as the equilibrium pressure of the LP storage (the pressure at which refueling shifts from Line 1 to Line 2) influences the HRS costs, and in Table B-1 a sensitivity analysis is carried out with these variables.

With respect to the compressors, the LP compressor is dimensioned to serve the WE system (flow of 1600 kg/day) while the HP compressor capacity depends on several system design parameters. According to findings in previous studies addressing design- and cost optimizations of hydrogen refueling systems[2], as well as general recommendations to ensure prolonged compressor lifetime[3], we have designed the system with as small as possible compressor throughput.

Generally speaking, a higher pressure of the LP bank makes the LP compressor more costly but reduces the costs of the HP compressor. Furthermore, having an equilibrium pressure of 200 rather than 150 bar means that a larger LP storage is required, but simultaneously that the HP storage and HP compressor work is reduced. The figure shows that a LP storage at 300 bar and drawing this down to 200 bar before switching to Line 2 yields the most cost-effective configuration.

Table B-1 Levelized cost of hydrogen (NOK/kg$_{H2}$) of HRS components for various LP storage bank pressures (rated/maximum pressures and equalization pressures after refueling bus) and HP compressor capacities.

Rated LP pressure (bar)	**250**		**300**	
Equilibrium pressure (bar)	**150**	**200**	**150**	**200**
HP compressor (NOK/kg)	0,34	0,31	0,30	0,27
LP compressor*	12,46	12,46	12,47	12,47
LP storage (NOK/kg)	0,75	2,25	0,58	1,31
HP storage (NOK/kg)	3,68	2,84	3,68	2,84
SUM (NOK/kg)	**17,23**	**17,86**	**17,03**	**16,90**
Installed H2 capacity (LP/HP storage) (kg)	1207/3698	3620/2857	939/3698	2113/2857

* Alkaline water electrolyzer assumed, meaning the suction pressure of the LP compressor is 5 bar.

Hydrogen produced by an external production facility might offer a range of benefits, including cheaper costs, however it inflicts additional costs in form of transport. A relevant transport solution is by storing it in pressurized tanks and transport it with hydrogen transport modules. Companies such as Hexagon or Umoe Advanced Composites offer commercially available solutions for hydrogen transport modules, see Figure B-1.

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[1] Parks, G., et al., *Hydrogen Station Compression, Storage, and Dispensing – Technical Status and Costs*. 2014, National Renewable Energy Laboratory.

[2] Reddi, K., et al., *Two-tier pressure consolidation operation method for hydrogen refueling station cost reduction.* International Journal of Hydrogen Energy, 2018. **43**(5): p. 2919-2929.

[3] Reuter, B., et al., *New Bus Refuelling for European Hydrogen Bus Depots: High-Level Techno-Economic Project Summary Report.* Fuel Cell and Hydrogen Joint Undertaking: Brussels, Belgium, 2017.

Figure B-1: Two transport solutions of hydrogen by truck in 20ft and 40ft containers/semitrailers[4,5]

For delivered hydrogen, a sensitivity analysis has been carried out considering 20- and 40-foot size and 300 and 500 bar pressure. When considering the cost of transport, including man hours[6] and a fixed lifetime of 20 years a levelized cost for only transport was calculated and a sensitivity analysis made over central assumptions. The results are shown in Figure B-2. In the reference case it is assumed transport of 100 km, delivering 1000 kg hydrogen five times per week and an interest rate of 4%.

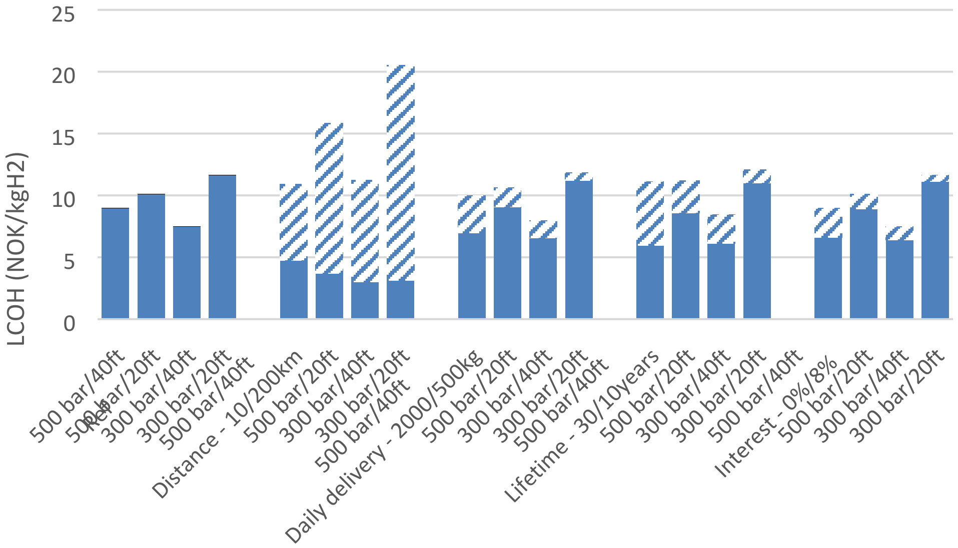

Figure B-2: The levelized cost of transport for different tube-trailer solutions.

The analysis shows that in most cases a **40-foot hydrogen transport module transporting hydrogen at 300 bar is the most feasible alternative**, despite the increased payload when transporting H_2 at 500 bar. In the reference scenario it adds a cost of 7.5 NOK for each kg hydrogen transported. The strongest impact on the cost is the distance required to transport the hydrogen and makes the cheapest alternative fluctuate between -60% to +50% if the transport distance changes between 10 and 200 km. When the transport need is 200 km, the 40-foot and 500 bar hydrogen transport module solution become a slightly cheaper alternative.

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[4] https://www.uac.no/container-transportation-solutions/hydrogen/

[5] https://hexagongroup.com/solutions/storage-distribution/hydrogen/

[6] https://www.toi.no/publikasjoner/kostnadsmodeller-for-transport-og-logistikk-basisar-2016-article35060-8.html

Appendix C - Dynamic modelling of HP storage

The main calculation tool in this work is based on static modelling of the HRS including HP compressor work between an averaged suction pressure of 200 bar and an averaged delivery pressure of 425 bar. To dimension the HP storage, a dynamic model has been implemented for compressor, HP bank and refueling demand with 1 min resolution over three working days (72 hours).

It is complicated to model hydrogen in detail due to its specific thermodynamic behavior and heat exchange with the system. In addition, there are many components in the supply chain, which are interdependent. To limit the complexity of the model the following simplifications have been made:

- Constant LP storage pressure at 200 bar
- Constant temperature of hydrogen at 15 °C
- Power for compression is based on adiabatic compression equation:

$$W = \left[\frac{\gamma}{\gamma - 1}\right] * P_0 * V_0 * \left[\left(\frac{P}{P_0}\right)^{\frac{\gamma - 1}{\gamma}} - 1\right] \qquad (C\text{-}1)$$

  where P_0 is the initial pressure (Pa), V_0 is the initial specific volume (m^3/kg), P is the end pressure (Pa), and γ=1,41 is the adiabatic coefficient[9]. In addition, the mechanical efficiency of the compressor is assumed to be 70 %, including intercooling or other auxiliary systems.

The model includes: (i) one HP compressor, (ii) three HP storage tanks, (iii) two valve assemblies, the first controlling which tank the HP compressor is working against, and the second controlling from which tank hydrogen is withdrawn during refueling or if possible allowing direct overflow from LP storage.

A valve switchboard lets the HP compressor alternate between which of the three HP storages it replenishes, following a simple logic for every timestep:

1. If no HP tank is above 400 bar, replenish the tank with highest pressure
2. If the tank which was replenished in previous time step has reached max pressure (450 bar), start to replenish the tank with least pressure.
    a. If all tanks have reached max pressure, don't run the compressor in current time step
3. If previous steps where not true; continue to replenish the same tank as in the previous time step.

The dynamics presented in this model are mainly reflecting how the mass transfer capacity of the compressor, with a fixed power input, changes over time as pressure in the HP tanks varies due to the demand. The HP storage capacity plays an important role due to following dynamics, which can lead to oversizing the compressor:

- With a too small HP storage the hydrogen buffer amount becomes too small during peak hours and the compressor cannot maintain sufficient pressure in the HP storage system.
- With a too large HP storage the compressor spends too much time to top-up the tank with highest pressure with relatively small mass flow. Consequently, the compressor will not have enough time to refill HP tanks with lower pressure at a larger mass flow rate. This leads to failing to transfer enough hydrogen to the HP storage within a day.

The dynamics make the compressor and storage sizes interdependent and the objective is to minimize the size of both components. However, the size of the compressor is prioritized as it is a more expensive component. The system is designed to fulfil two requirements: (i) at any time provide a

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[9] Stolten, D. (2010). *Hydrogen and fuel cells: fundamentals, technologies and applications*: John Wiley & Sons.

minimum pressure for HP storage of 350 bar and (ii) that the mass of hydrogen in HP storage after the modelling period is equal or higher than the mass at the starting conditions. Based on these criteria, the storage system was modelled according to demand from slow and fast fill, with a starting condition where the three HP tanks have a pressure level of 300, 400 and 450 bar. For each case three different balance points between compressor and HP storage size were identified.

Slow fill

For slow fill, the smallest feasible compressor size was identified to be 8 kW and sizes up to 10 kW was considered, as shown in Table C-1. In Figure C-1 is shown the dynamics of 8 kW compressor with 825 kg$_{H2}$ storage. When compressor size increases with 25 % from 8 to 10 kW, the storage size decreases with 31 %. In addition, some more flexibility in the system gets unlocked with increased compressor size as the average pressure (and mass) in the HP storage increases at the end of the period in comparison with starting conditions and longer stand-still periods of compressor.

Table C-1 viable compressor and HP storage sizes from dynamic modelling and complementary model results

Compressor size (kW)	HP storage size (kg$_{H2}$)		Min pressure in HP storage (bar)	Increase in mass of hydrogen stored in HP storage at the end of time horizon (kg$_{H2}$)	Compressor standing still (% of time)
	Per tank	Total			
8	275	825	367	0	0%
9	211	633	352	22	3%
10	191	573	351	25	12%

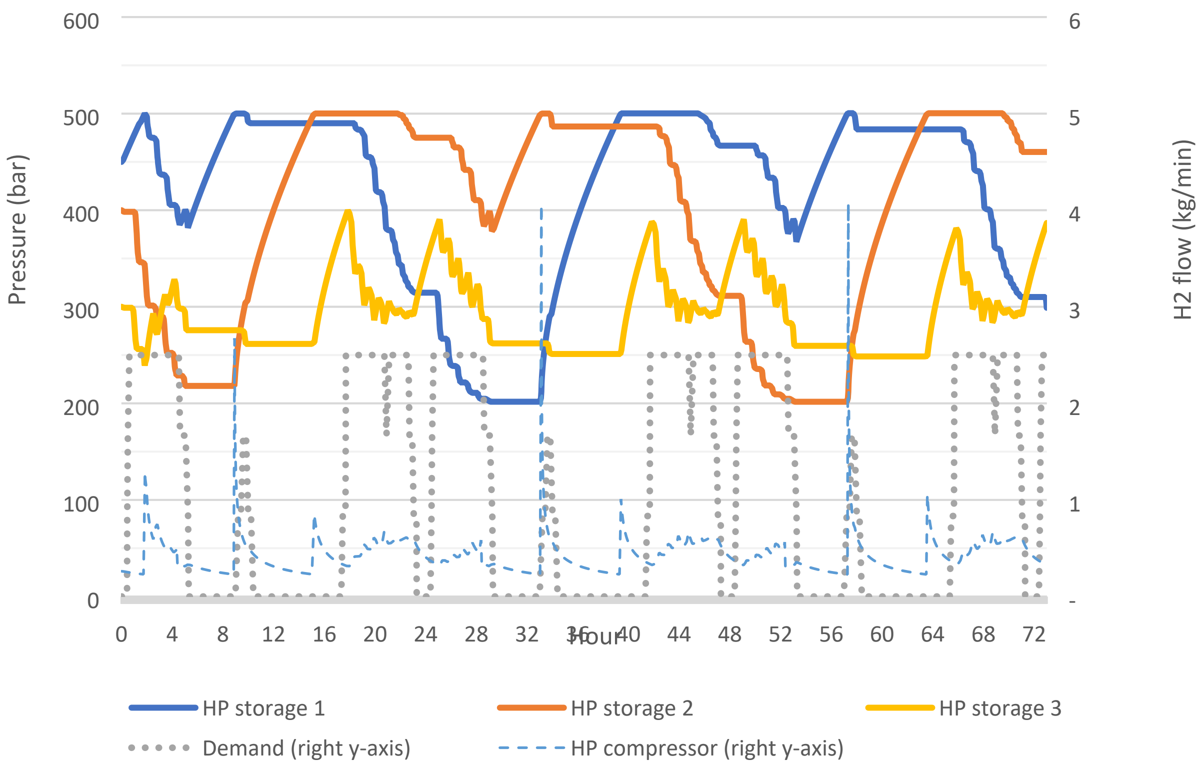

Figure C-1 Variation in pressure for the three HP storage tanks and in the flow of both compressor and demand for a slow fill system.

Fast fill

For fast fill, the smallest feasible compressor size was identified to be 9 kW and sizes up to 11 kW were considered, as shown in Table C-2. In Figure C-2 is shown the dynamics of 9 kW compressor with 11 kg_{H2} storage. When compressor size increases with 25 % from 8 to 10 kW, the storage size decreases with 27 %. In addition, some more flexibility in the system gets unlocked with longer stand-still periods of the compressor.

Table C-2 viable compressor and HP storage sizes from dynamic modelling and complementary model results

Compressor size (kW)	HP storage size (kg_{H2})		Min pressure in HP storage (bar)	Increase in mass of hydrogen stored in HP storage at the end of time horizon (kg_{H2})	Compressor standing still (% of time)
	Per tank	Total			
9	300	900	355	18	0%
10	225	675	354	2	8%
11	211	633	359	7	15%

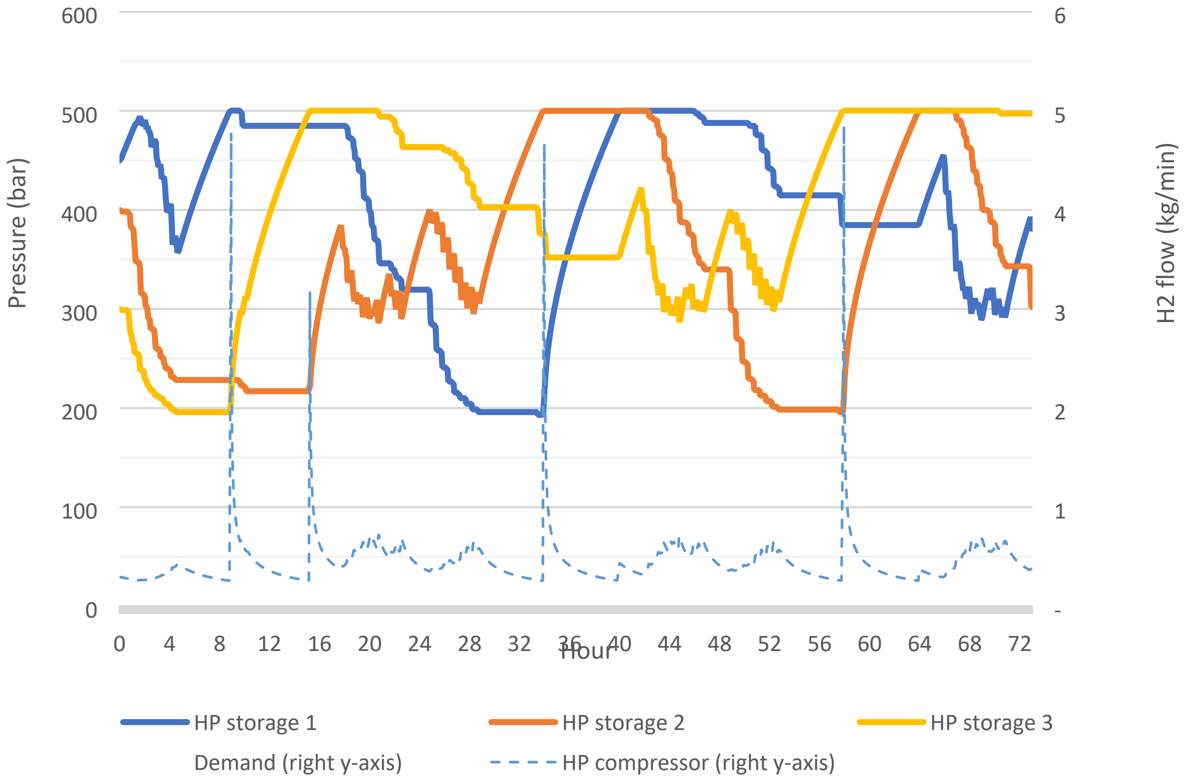

Figure C-2 Variation in pressure for the three HP storage tanks and in the flow of both compressor and demand for a fast fill system.

Conclusion

The simulations show that for this specific demand at the bus depot and with intention to minimize the main cost driver, the compressor size, at slow-fill design both the compressor and storage can be decreased by 11 % and 8 % respectively in comparison with fast-fill. The reduction in capacities will also decrease their physical footprint.

These results must be seen in the light of several simplifications of the reality, where a more detailed evaluation of aspects such as minimum pressure difference at overflow, number of HP storage tanks, hydrogen temperature, hydrogen heat exchange and dynamic LP storage pressure could improve the precision of the results.

In comparison with static simulation of the slow-filling HRS the dynamic modelling suggests that the size of the compressor for slow fill needs to be increased by 14 % to 8 kW, while the storage size can be decreased by 71 % to 825 kg_{H2}. It demonstrates that in this proof-of-concept analysis, static dimensioning of the compressor in an HRS could provide a first estimate which lies within a 20 % error margin, while a large deviation was found for HP storage.

Tittel: Efficient hydrogen infrastructure for bus fleets – Evaluation of a slow refueling concept for bus de

Dokumentklasse:

Signaturer:

Author:	Janis Danebergs ife.no\janis.danebergs	2020-12-01 10:25:13 (UTC+00:00)
Author:	Ragnhild Hancke ife.no\Ragnhild.Hancke	2020-12-01 10:32:12 (UTC+00:00)
Author:	Lisa Kvalbein ife.no\lisa.kvalbein	2020-12-01 15:41:40 (UTC+00:00)
Author:	Fredrik Aarskog ife.no\Fredrik.Aarskog	2020-12-01 20:45:13 (UTC+00:00)
Review Approval:	Øystein Ulleberg ife.no\Oystein.Ulleberg	2020-12-02 09:05:06 (UTC+00:00)
Content Approval:	Arne Lind ife.no\Arne.Lind	2020-12-07 18:39:08 (UTC+00:00)