NEXT NORDIC GREEN TRANSPORT WAVE - LARGE VEHICLES

Detailed analysis for large-scale hydrogen transport in Finland

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Table of contents

Next wave - about the project

Electrification of the transport sector already began and the Nordic countries, specifically Norway and Iceland, have taken major steps resulting in battery electric vehicles (BEVs) already accounting for a substantial percentage of the total sales. The world is looking towards the Nordics as they are providing global examples for success. However, little is happening regarding larger vehicles as battery solution still are not able to provide heavy-duty users (e.g., buses, trucks, and lorries) the mobility they need.

Fuel cell electric vehicles using hydrogen as a fuel can solve this. The project focuses on providing infrastructure for a large-scale deployment of trucks, buses, and lorries. The goal is to further stimulate the global technological lead, which the Nordic countries have by stimulating the very first hydrogen infrastructure roll-out for larger vehicles while at the same time map how the infrastructure build-up needs to be done, so that the transition to hydrogen vehicles can happen smoothly. Such roll-out will also benefit the use of hydrogen for trains and the maritime sector. Furthermore, in addition of sourcing the hydrogen as a by-product from the industry, in the Nordic region we have the unique opportunity to produce the hydrogen in a green manner exploiting renewable electricity production.

Already, Nordic industries have taken international lead in the field of hydrogen and fuel cells and a unique cooperation exists between "hydrogen companies" via the Nordic Hydrogen Partnership (former Scandinavian Hydrogen Highway Partnership, SHHP) cooperation. Jointly they have marketed the Nordic platform for hydrogen and, at the same time, paved the way for vehicle manufacturers to deploy such vehicles in the Nordic countries. When it comes to hydrogen, the Nordics have globally leading companies both within the infrastructure and the fuel cell business. The project therefore sets forward four key activities in a unique project where technical innovation and deployment strategies are intertwined.

The project will deliver an analysis on large-scale transport of hydrogen with mobile pipeline, a description of the innovation and business potential for a roll-out of FC-buses in the Nordic region, as well as a coordinated action plan for stimulating the FC truck demand and a prospect for utilising hydrogen in heavy-duty equipment. Finally, the project will contribute to national and Nordic hydrogen strategy processes even providing input to a possible Nordic Hydrogen Strategy.

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Summary

In the report, analysis on large-scale transport of hydrogen with mobile pipeline (gas container or trailers) from hydrogen production points to consumer locations is described. The detailed analysis has been carried out for Finland and this analysis is applicable for other Nordic countries when national regulations and price levels are taken into account.

The analysis is done focusing on hydrogen transport to large-scale hydrogen refuelling stations (HRS), since when The European Commission published a proposal «Fit for 55» package (July 14, 2021) there was a proposal obligatory network of HRS along TEN-T core network by 2030. However, the results are partly applicable also for large-scale transport of hydrogen to the industry customers.

Regarding HRS, the mobile pipeline for hydrogen is part of the hydrogen supply chain (HSC). An alternative to the mobile pipeline is hydrogen production by local electrolysis. These alternatives are compared for Finland.

The results show that when semi-centralised option for hydrogen production is analysed and the hydrogen is transported to HRS locations within 300 km, the price estimate is just below 6 €/kg of hydrogen. In the case of on-site electrolysis, the price estimate is close to 10 €/kg of hydrogen. These cost levels of hydrogen could be further reduced especially if production and dispensing costs could be reduced.

Photo: Geran De Klerk, Unsplash

Background

When hydrogen is delivered for cars, trucks, buses, and lorries, a range of different options for the hydrogen supply chains (HSC) exists. The three main options are transport by tube trailers, by pipelines, or as cryogenic liquid hydrogen.

When hydrogen infrastructure for transportation is being deployed, the demand is relatively low in the beginning. This is the typical situation in most of the countries these days (2021). Hydrogen transport by tube trailers from production point to the hydrogen refuelling station (HRS) is in this case the only feasible option.

When the overall hydrogen demand for transportation increases, the distribution by pipeline or even as liquid hydrogen becomes worth considering. However, if the total number of HRSs is not very large, but the HRS of interest is large in size, the use of local electrolyser for hydrogen production on-site the HRS becomes an alternative to hydrogen transport by means of tube trailers.

If HRS is using electrolyser for on-site hydrogen production, tube trailers might still be needed to cover peak demand as well as for backup purposes. This combination increases the security / redundancy of hydrogen supply, especially if the delivery pressure level is 500 bar, which currently is the highest pressure used in tube trailers. In this case, vehicle refuelling even without compressor at HRS is possible.

Thus, green hydrogen can either be produced on-site next to the HRS using small electrolyser or produced in more centralised way using a large electrolyser and transported to the HRS using tube trailers.

The choice between different alternatives is dependent on numerous parameters, such as:

- Electrolyser cost as a function of electrolyser size.
- Hydrogen compression cost as a function of compressor size.
- Transportation cost:
    - Transportation distance.
    - Maximum payload of hydrogen in tube trailer.
    - Tube trailer capital cost.
- Hydrogen storage cost and regulation.

The cost target for green hydrogen used in heavy-duty vehicles should be under 6 €/kg of hydrogen, delivered in vehicle tank at 700 bar. For 350 bar, the cost target should be even lower.

When consumption is large enough, the most cost-effective way to provide all the hydrogen will be the electrolyser option, assuming that electricity grid is strong enough. Otherwise, transport of at least part of the hydrogen will be included.

Therefore, it is important to identify the existing and future industrial hydrogen production points and possibilities to transport hydrogen from them to the small and mid-size HRS (consumption points).

The industrial hydrogen production points used here are based on the Next Wave delivery reports D2.1 and D2.2. The estimates for the hydrogen transportation cost are partially based on the delivery report D2.3, while the most interesting case studies for all Nordic countries are discussed in D2.4.

It is assumed that hydrogen sold and delivered to HRS will increase the size of centralised industrial electrolyser, for example from 100 MW to 110 MW. Therefore, the capital investment is much smaller than for a separate 2 MW electrolysers (located on-site). This analysis also assumes that the average electricity price for centralised electrolysers is lower than electricity price for on-site electrolysers, as centralised electrolysers are connected to transmission grid while on-site electrolysers are connected to distribution grid.

For by-product hydrogen, large initial demand for hydrogen is needed to justify the investments for purification. Furthermore, there are large variations and uncertainties related to such purification costs. Therefore, the calculation is done only for centralised industrial electrolysers and on-site electrolysers.

The cost calculations in this work are done for the case that hydrogen is dispensed at the pressure level of 350 bar intended for heavy-duty vehicles (mostly trucks). In Finland, the dimensions of trucks allow the use of 350 bar pressure level without significant loss of payload, as cargo weight (not volume) is typically the limiting factor.

Hydrogen distribution cost at refuelling station

The cost of hydrogen supply and distribution to vehicles has been a topic of numerous scientific as well as commercial studies[1], either for hydrogen delivery to the station, hydrogen dispensing at the station, or for both. In addition to scientific literature, cost estimates were given in a recent fuel cell hydrogen heavy-duty truck study for 350 bar and 700 bar which are summarised in *Table 1* (FCH-JU 2020).

Table 1. Cost data of hydrogen (€/kg, excl. margin) from H2FC HDT study (FCH-JU 2020) for PEM electrolyser (PEMEL)

bar (year)	Production	Conditioning	Transport	Refuelling	Total
350 (2023)	3.5	0.8	0.9	1.5	6.7
350 (2030)	2.4	0.5	0.7	0.7	4.3
700 (2023)	3.4	0.8	0.8	1.9	6.9
700 (2030)	2.5	0.5	0.7	1.0	4.7

In addition to models and data from the scientific literature and reports, there are freely available excel-based tools for the calculation of techno-economic assessment of refuelling for a fleet of heavy-duty fuel cell electric vehicles (HEAVY-DUTY REFUELING STATION ANALYSIS MODEL, HDRSAM)

1 https://www.lazard.com/media/451779/lazards-levelized-cost-of-hydrogen-analysis-vf.pdf

and light-duty fuel cell electric vehicles (HYDROGEN REFUELING STATION ANALYSIS MODEL, HRSAM). The schematic overview of the HRSAM model is shown in *Figure 1*. The models have been in several reports by Argonne National Laboratory and also in scientific publications (Reddi et al. 2017).

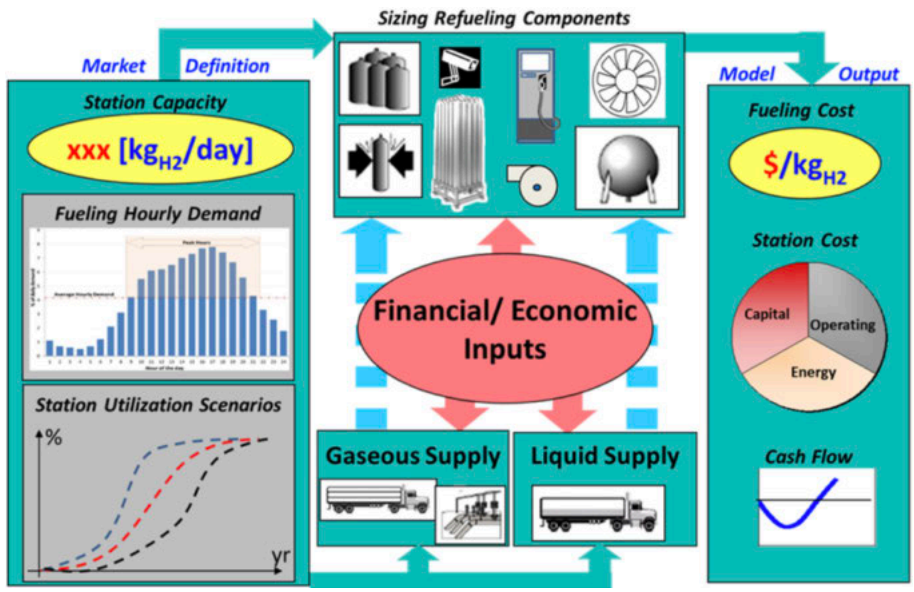


Figure 1. Schematic overview of the HRSAM model[2].

The HDRSAM model was released for public in 2017, hence, the cost parameters for the distribution can be considered relatively up-to-date, even if the model is meant for use in USA. The results of HDRSAM are used to compare the difference between 350 bar and 700 bar dispensing options, as well as illustrating the economics of scale for hydrogen dispensing, *Table 2*.

The assumption for the HDRSAM model is that the demand for hydrogen is 1,000 kg/day. That is, 20 heavy-duty vehicles, 50 kg hydrogen each visiting the HRS daily, and refuelling is assumed to be evenly distributed between 7 am and 7 pm. The results show that the dispenser adds 0.08 USD/kg, and refrigeration 0.06 USD/kg and 0.11 USD/kg for 350 bar and 700 bar output pressures, respectively. Electricity cost is approximately 0.06 USD/kg and controls approximately 0.19 USD/kg for all cases.

Table 2. Cost (USD/kg) of hydrogen dispensing from HDRSAM model

P_{in} / P_{out}	Compressor	Storage	Other (incl. refrigeration, electricity)	Total	Total ($/kg)
20 bar / 350 bar	0.87	0.86	0.40	2.13	1.9
20 bar / 700 bar	1.57	1.18	0.46	3.21	2.8
500 bar / 350 bar	0.61	0.45	0.42	1.48	1.3
500 bar / 700 bar	1.27	0.78	0.46	2.51	2.2

2 https://hdsam.es.anl.gov/index.php?content=hrsam

The results of HDRSAM study as well as HDT study (FCH-JU 2020) indicate that the difference in delivery cost of hydrogen is not very large (about 1 €/kg) when pressure is increased from 350 bar to 700 bar and the amount of dispensed hydrogen is large enough (1,000 kg/day).

However, here, the effect of station reliability is not accounted for. For a 700 bar station, a cooling system is required and the booster compressor must work harder. Thus, in order to reach the same reliability with 700 bar as for 350 bar, the 700 bar station configuration should be different, including redundant components. The reliability of the station is an important issue, when the total number of stations is limited.

Hydrogen transportation

As described in the Next Wave delivery report D2.4, the main logistic option for hydrogen transport today is trucked compressed gas. Road transport has been considered to be the most suitable for delivery of relatively small amounts of hydrogen for short or moderate distances up to 300 km (Lahnaoui et al. 2019; Yang and Ogden 2007).

Due to development of fiberglass and carbon fibre composite cylinders, there has been increase of payloads from 200-300 kg up to 1,000 kg with 40 tonne trucks (Lahnaoui et al. 2019). At the same time, the pressure level has increased from the traditional 200 bar up to 500 bar enabling more compact storage. Even 1,000 bar transport solutions are studied in the German H_2-HD project[3]. The use of 1,000 bar in transport would almost completely eliminate the need of compressor at HRS dispensing hydrogen at 700 bar, while the use of 450-500 bar in transport would do the same for hydrogen dispensed at 350 bar pressure level.

When these new options have been used in the latest HSC analyses, it has been noticed that the cost-efficiency of hydrogen transport by tube trailers has increased significantly (Andresen, Bode, and Schmitz 2018; Lahnaoui et al. 2018; Reuß et al. 2017; Ulleberg and Hancke 2020).

The use of tube trailers may be the first step in building the hydrogen infrastructure. Then, when the demand increases, they can be partially replaced by pipelines, on-site electrolysers, or with liquid hydrogen supply options. Tube trailers should always complement on-site production of hydrogen in hydrogen refuelling stations, increasing security of hydrogen supply. The use of hydrogen tube trailers (gas containers) is flexible; the containers may first serve one location before being moved to serve another location.

[3] https://www.imws.fraunhofer.de/en/presse/pressemitteilungen/hypos-pressure-tanks-green-hydrogen.html

Cost model for hydrogen production and compression

In this report, three cases are considered:

- Distributed on-site production (1,000 kg/day).
- Semi-centralised production (5,000 kg/day).
- By-product hydrogen (Joutseno, Äetsä).

Distributed on-site production (1,000 kg/day)

In this case, an on-site hydrogen production is considered. The demand of hydrogen is assumed to be 1,000 kg/day. Hence, the electrolyser size is assumed to be 2 MW as electrical power. The cost of the hydrogen production is based on the literature model described in detail below. Basic assumptions for the model are:

- Electrical efficiency of the electrolyser: 62%.
- Utilisation rate: 40%.
- Electricity price: 50 €/MWh (distribution medium voltage grid).
- Cost for distributed hydrogen is based on the literature models.

Semi-centralised production (5,000 kg/day)

Here, a semi-centralised production of hydrogen to transportation use as part of other industrial production is considered. It is assumed that an "additional hydrogen electrolyser capacity" of 100 MWe is used for supply of hydrogen to HRSs. Thus, the capital investment cost is only a fraction of the whole investment cost. Basic assumptions for this model are:

- Utilisation rate: 80% (a high utilisation rate is assumed due to industry demand).
- Electricity price: 30 €/MWh (high voltage transmission grid).
- Continuous compression (trailer filling) from buffer storage is possible.

By-product hydrogen (Joutseno, Äetsä)

There are two interesting possibilities to utilise by-product hydrogen from chlorate and chlor-alkali production in Finland. As chlorate and chlor-alkali plants are typically operated throughout the year at close to the maximum capacity, the full load hours (FLH) for the hydrogen production and consumption processes could be assumed to be 8,500 hours/year. The price (value) for hydrogen is the same as for natural gas (incl. CO_2 fees), as hydrogen would replace natural gas, wood chips, or electricity (heat pumps) in heat production. A price of 1 €/kg could be assumed for this purpose.

In Äetsä, the amount of by-product hydrogen, which has already a purification system, is 2-3 tonnes/day, hence 1,000 tonnes/year. However, some additional purification is needed, which also has a cost (0.5-1 €/kg).

In Joutseno, the amount of hydrogen from chlor-alkali plants could be 5-6 tonnes/day resulting in up to 2,000 tonnes/year. This hydrogen can be assumed to be pure enough for HRS utilisation, hence no additional purification costs would be necessary. However, if by-product hydrogen from chlorate production is used, then additional purification is needed as in Äetsä.

The calculation example in this report is done only for semi-centralised production by industrial electrolysis. A similar calculation example could be done using by-product hydrogen, which is available from two locations (Joutseno, Äetsä). In this case, however, the total amount of hydrogen available is limited to 2,000-4,000 tonnes per year. The total available by-product can be up to 10,000 tonnes. However, significant additional investments for hydrogen purification and compression would be needed.

Hydrogen transportation

Production of hydrogen by PEM electrolysers with an efficiency of 62% (η_{PEMEL}) based on the lower heating value (LHV) of hydrogen is considered. The selection of a PEM electrolyser over alkaline electrolyser was done due to its ability to produce hydrogen at elevated pressure (here assumed to be 20 bar) so that results for on-site and centralised production would be more easily comparable. In practice, PEM electrolyser may be more commonly used in on-site productions, while alkaline electrolyser may be used for centralised production.

The total investment costs (IC_{PEME}) for the 2 MW and the 100 MW hydrogen demands were estimated to be 2.3-3.5 M€ and 60-89.8 M€, respectively, by using *Eq. 1* below. The investment costs include cost for installation, building, piping, and grid connection. The price estimations for PEM electrolyser systems were taken from the Lazard study[4] (for 1 MW, 20 MW, and 100 MW systems), and least-squares method was used to optimize the scaling factor (here 0.83). *Table 3* shows the estimated values for low, medium, and high CAPEX values.

$$IC_{PEME} = IC_{ref}\left(\frac{P_{PEME}}{P_{ref}}\right)^{0.83} \qquad \text{Eq. 1}$$

where

IC_{ref} = specific capital cost when electrolyser has reference size (p_{ref})
p_{PEME} = size of the electrolyser
p_{ref} = reference size

Table 3. Estimated CAPEX of different size PEM electrolysers

Size	Low price	Medium price	High price
2 MW	2.3 M€ (1,150 €/kW)	2.9 M€ (1,450 €/kW)	3.5 M€ (1,750 €/kW)
100 MW	60 M€ (600 €/kW)	74.2 M€ (742 €/kW)	89.8 M€ (898 €/kW)

4 https://www.lazard.com/media/451779/lazards-levelized-cost-of-hydrogen-analysis-vf.pdf

Investment costs (IC) were annualised using the Capital Recovery Factor (CRF) method using an interest rate (i) of 8% and a process specific lifetime (n) of 15 years, *Eq. 2*. Annualised investment costs (IC_{annual}) are obtained by multiplying the investment costs (IC) by the Capital Recovery Factor (CRF), *Eq. 3*.

$$CRF = \frac{i \times (1+i)^n}{(1+i)^n - 1} \quad \text{Eq. 2}$$

$$IC_{annual} = CRF \times IC \quad \text{Eq. 3}$$

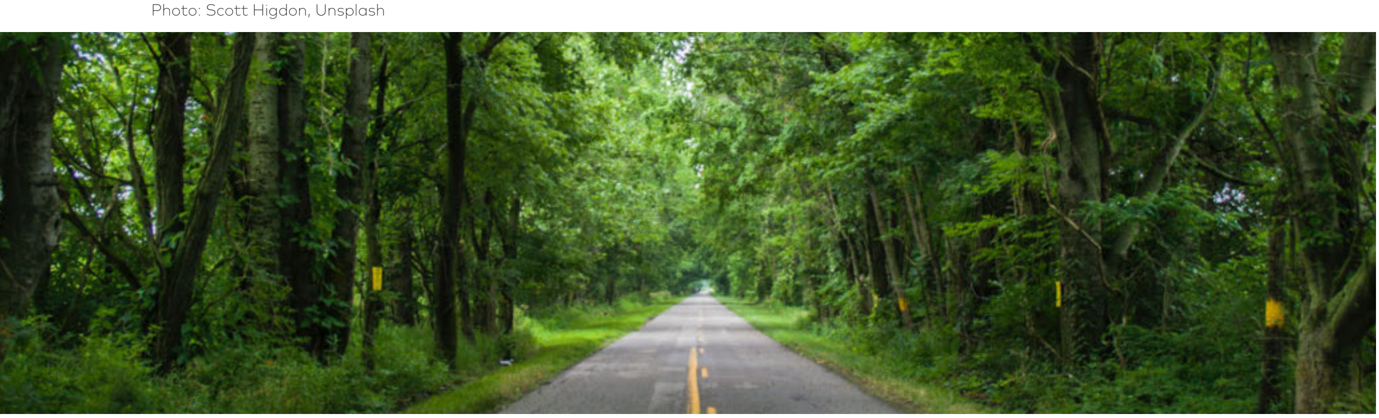
Fixed operation, and maintenance costs (FC_{PEME}) were assumed to be 5% of investment costs including stack replacement costs. Neither oxygen nor low-temperature heat from the water electrolysis had any additional value in this case. Full load hours (FLH) for the hydrogen production were assumed to be 8,500 hours/year. Utilisation rate (UR) was analysed between 30% and 100%. Electricity price for 2 MW and 100 MW electrolysers were 50 €/MWh and 30 €/MWh, respectively, based on Finnish electricity prices for small- and large-scale industrial customers. The specific cost of PEM electrolyser produced hydrogen (SC_{PEME}) was calculated using *Eq. 4*.

$$SC_{PEME}\,(€\,kg^{-1}) = \frac{IC_{PEME} \times (CRF_{PEME} + FC_{PEME}) + Hydrogen_{out}\,(MW) \times Electricty\ price \times FLHxUR}{Hydrogen_{out}\,(MW) \times FLHxUR \times \eta_{PEME}} \quad \text{Eq. 4}$$

The results of specific cost of PEM electrolyser produced hydrogen are illustrated in *Figure 2*. For centralised production, the production cost is approximately 2.5 €/kg (80-90% utilisation rate), while for on-site electrolysis typically operating at 40% utilisation rate the production cost is about 6-7 €/kg of hydrogen. The price of electricity is estimated to be 20 €/MWh higher for on-site electrolyser based on Finnish prices for small and large industrial users.

The price of electricity has drastic effect on the specific price of hydrogen, and for that reason, it is essential to produce hydrogen at low electricity prices.

Photo: Scott Higdon, Unsplash



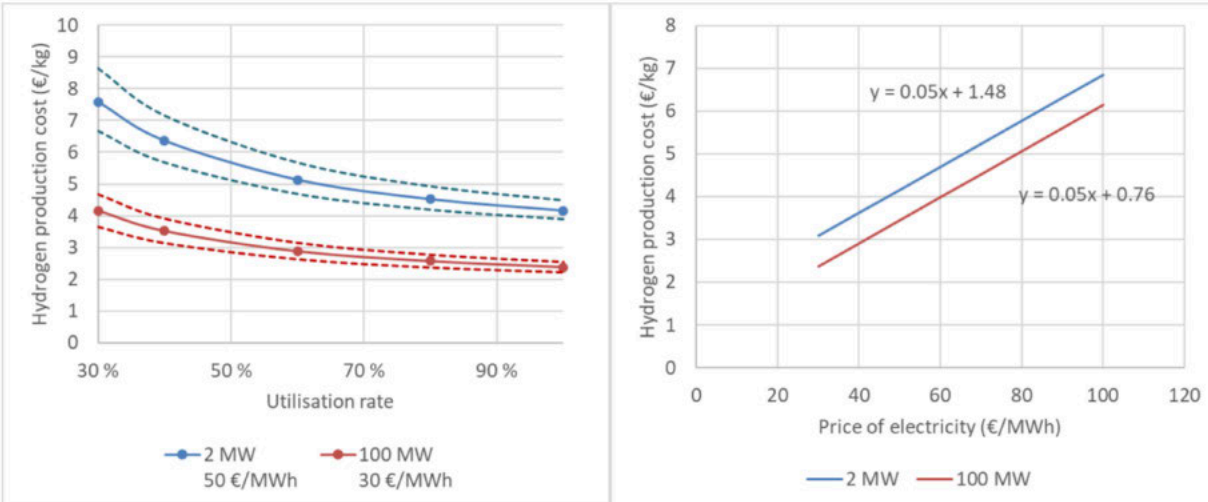


Figure 2. Left: Specific cost of PEM electrolyser hydrogen for 2 MW and 100 MW systems at different utilization rates. Dashed lines indicate low and high (CAPEX) cost estimates. Right: Specific cost of PEM electrolyser produced hydrogen for 2 MW and 100 MW systems at different electricity prices. Medium CAPEX and 100% utilisation rate.

Hydrogen compression cost model

Hydrogen compression energy as well as compressor capital costs are based on the methodology used by Hurskainen and Ihonen (Hurskainen and Ihonen 2020).

Compression work

The specific work (W, kJ/kg H_2) for compressors was calculated using *Eq. 5*. The number of compression stages was determined based on the maximum compression ratio of 2.5. Intercooling to 40°C between stages was assumed.

$$W_{comp} = \frac{ZRT_1}{M}\frac{N\gamma}{\gamma-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{N\gamma}} - 1\right]\eta^{-1} \qquad \textit{Eq. 5}$$

where

- Z = compressibility factor
- R = universal gas constant (8.3145 J/(mole K))
- T_1 = suction temperature (313.15 K)
- M = molar mass of hydrogen (2.016 g/mole)
- p_1 = suction pressure
- p_2 = discharge pressure
- N = number of compressor stages
- η = isentropic efficiency (75%)
- γ = specific heat ratio (C_p/C_v) (1.41)

The compressor discharge pressure ($p_{2,filling}$) was calculated by logarithmic mean of the maximum (p_{max}) and minimum pressures (p_{min}), *Eq. 6*:

$$p_{2,filling} = \frac{p_{max} - p_{min}}{log\left(\frac{p_{max}}{p_{min}}\right)} \quad \textit{Eq. 6}$$

This approach considers that the discharge pressure increases towards the maximum value as the tank fills up, rather than being constantly at the maximum value. In other words, the compressor discharge pressure follows the pressure in the storage tank.

The minimum pressure for composite cylinders was set to 5 bar and maximum pressure 500 bar. In practice, the minimum pressure is dependent on the tank type and manufacturer as well as operation of the refuelling station.

Annual electricity costs of compression ($EC_{ann,comp}$) were calculated from the specific work of compressor, annual hydrogen production, and electricity price, *Eq. 7*:

$$EC_{ann,comp} = W_{comp} \times Annual\ hydrogen\ production \times Electricy\ price \quad \textit{Eq. 7}$$

Capital cost for compression infrastructure

In capital cost calculations two different cases are calculated, the **filling centre** and **compressor skid**.

Filling centre is the physical infrastructure needed to fill gas bundles and/or tube-trailers (typically 100-200 kg/h). Hence, it is the physical interface with the hydrogen logistical system. Filling centres include compressor skids, piping, and filling equipment.

Compressor skid is needed at on-site hydrogen production HRSs to pressurize the hydrogen from the electrolyser outlet pressure to the on-site storage pressure. The compressor skid includes the compressors and the auxiliary components such as cooling and control systems.

The investment costs of both compressor skids (IC_{comp}) and filling centres were estimated using the methodology created in a study for the Fuel Cells and Hydrogen Joint Undertaking[5]. The model, *Eq. 8*, considers the site capacity (Q, kg/h), total pressure ratio (p_2/p_1) and final pressure (p_2):

$$IC_{comp} = A\left(\frac{Q}{Q_{ref}}\right)^a + B\left(\frac{Q}{Q_{ref}}\right)^b \left(\frac{p_2/p_1}{r_{ref}}\right)^c \left(\frac{p_2}{p_{ref}}\right)^d \quad \textit{Eq. 8}$$

[5] https://www.fch.europa.eu/sites/default/files/P2H_Full_Study_FCHJU.pdf

The constants used were the same as in the referred study (A_{skid} = 100 k€, A_{centre} = 550 k€, B = 300 k€, Q_{ref} = 50, r_{ref} = 200/30, p_{ref} = 200, a = b = 0.66, and c = d = 0.25).

For large-scale filling centres, the other CAPEX (incl. piping, engineering, buildings) was included to the model, however for on-site production additional other CAPEX (IC_{other}) was added to the investment cost model according to *Eq. 9*:

$$IC_{other} = 0.75\left(\frac{Hydrogen\ demand[kg/day]}{1800}\right)^{0.5} \qquad \text{Eq. 9}$$

Compressors were considered to have a lifetime of 15 years. Fixed O&M costs (FC_{comp}) were assumed to be 4% of the investment costs. Hydrogen losses were not considered as they are assumed to be minor and similar for each option. CFR was assumed to be the same as in the case of PEMEL. The specific cost of compression (SC_{comp}) in €/kg of usable hydrogen can then be written as *Eq. 10*:

$$SC_{comp} = \frac{IC_{comp}\times(CRF_{comp}+FC_{comp})+EC_{ann,comp}}{Annual\ delivered\ usable\ hydrogen} \qquad \text{Eq. 10}$$

It can be seen from the results in *Figure 3* that compression cost increases sharply as hydrogen demand decreases. Here it is assumed that utilisation factor for compressor is 100% in both cases. While very high (close to 100%) utilisation rate can be possible for filling centre, it will be much lower for on-site compressors. This will increase the capital cost of the compression, which is the dominating part of the total cost, especially, when daily compressed hydrogen amount is small.

Photo: Mike, Pexels

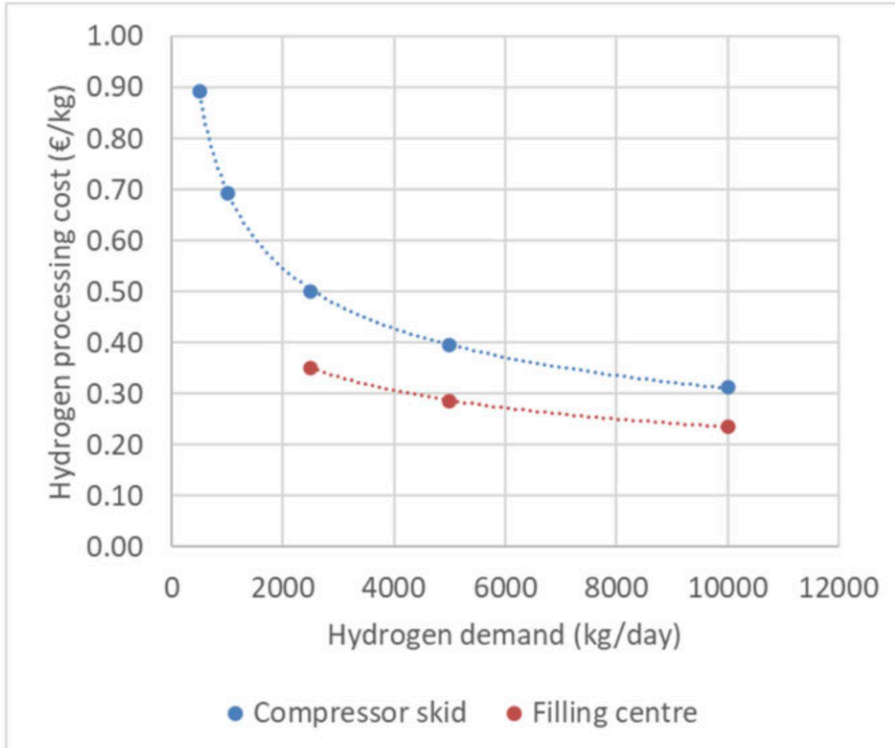


Figure 3. Hydrogen processing cost for compressor skids and filling centres (from 20 bar to 500 bar). Residual pressure in the containers assumed to be 10 bar. The price of electricity 40 €/MWh. The specific work for compressing containers from 10 bar residual pressure to 500 bar is 1 kWh/kg of hydrogen. Hence, if the price of electricity increases by 10 €/MWh it will increase the price of hydrogen by 0.01 €/kg.

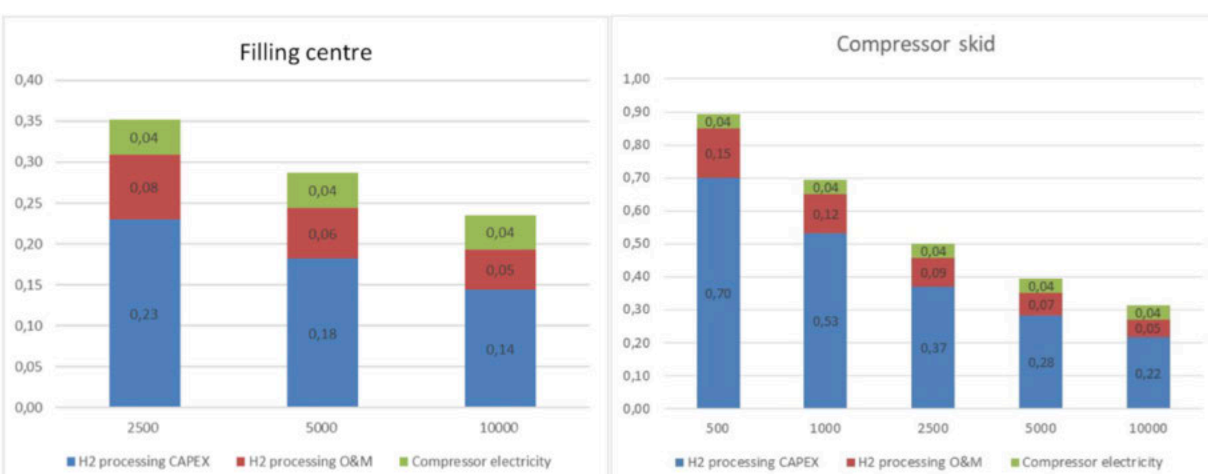


Figure 4. Cost components for hydrogen processing. Cost for compressor filling centres (left) and compressor skids (right).

Cost model for hydrogen transportation

The simple hydrogen transportation cost model is mostly based on the work of Hurskainen and Ihonen (Hurskainen and Ihonen 2020). The key parameters used for the compressors etc. are from other studies (FCH-JU 2020). The assumption is that hydrogen is transported from a major semi-centralised hydrogen production point to several HRS located within up to about 300 km range depending on the speed limits.

The initial purpose of the semi-centralised hydrogen production point is hydrogen production for industrial use. Therefore, the scale of production is very large (>> 10 tonnes/day) and can easily accommodate small extra production needed for several HRS (5 tonnes/day).

Another assumption is that the scale of production in each production point is sufficient to motivate investments for compressors and delivery equipment. In practice, the amount of hydrogen is 2-10 tonnes per day. In this study, 5 tonnes/day is selected. For example, by-product hydrogen from Joutseno (Finland) could be transported to the capital area (distance 250 km) and other HRS.

The goal of the analysis is to calculate transportation cost so that the hydrogen transport container also can be used as a storage at the HRS. This will reduce the cost of compressor and storage in the HRS, which should be modelled at some level.

Transportation of gaseous hydrogen

The transportation was modelled to take place with a B-link trailer configuration with two 40 ft containers, and varied distances shown in *Figure 5*. The average fuel consumption was assumed to be 50 litres/100 km. Factors used in modelling are presented in the Appendix.

Hydrogen is transported in carbon-fibre containers (500 bar, 1,000 kg of hydrogen) using tube trailers. The total amount of transported hydrogen per truck is 2 tonnes (hydrogen payload 1.5 tonnes). Pressurized hydrogen is transported to the hydrogen refuelling station (HRS). The empty back-haulage is also considered in the study.

The number of required deliveries per day depends on the hydrogen demand and net hydrogen payloads. Theoretical maximum number of trips for each truck per day will depend on unloading/loading (drop-off/pickup) times, transport distance, and average speed. Deliveries are assumed to take place 24/7 if necessary. It is assumed that the tube trailer full of hydrogen will be dropped off at the site and the empty one will be picked up.

The required number of trucks was calculated using the required number of deliveries and theoretical maximum number of trips each truck can make in one day and then rounding up to nearest larger integer. After rounding up, the lowest number of trips per day that meets the hydrogen demand is used in the analysis allowing non-integer numbers as well. For example, 0.5 trips per day could mean delivery every other day. In this analysis the number of trucks per each location is 1 and for that reason, the CAPEX costs are divided between each of the different routes.

The number of trailers (or hydrogen containers) needed for each route is assumed to consist of three parts: one trailer for transportation time, one trailer is being filled up at the hydrogen source (100 kg/h), and one trailer is being emptied at the hydrogen consumer site (42 kg/h). The trailers act as storage and, thus, no additional storage at the HRS is needed.

The specific delivery costs from trucking ($SC_{trucking}$) consist of investment costs for trucks and trailers ($IC_{trucking}$ and $CRF_{trucking}$), operation and maintenance costs ($SC_{trucking,O\&M}$), fuel ($SC_{trucking,fuel}$), and personnel costs ($SC_{trucking,personnel}$) as given in *Eq. 11*. The equations used to calculate the number of trucks and trailers required and trucking costs are given in the Appendix.

$$SC_{trucking}\ (€\ kg^{-1}) = \frac{IC_{trucking} \times CRF_{trucking}}{Delivered\ useful\ hydrogen\ per\ year} + SC_{trucking,O\&M} + SC_{trucking,fuel} + SC_{trucking,personnel} \quad \text{Eq. 11}$$

Investment costs for trucks and trailers includes hydrogen containers. The cost of different container types is discussed in *Next Wave deliverable 2.4*. Based on these discussions, the cost of gas containers should be between 400-800 €/kg of hydrogen depending on size, material, and pressure level. For the calculations in this deliverable, a cost of 550 €/kg of hydrogen is assumed for the containers.

Photo: Lex Valishvili, Unsplash

A selected case study for Finland

Analysis on large-scale transport of hydrogen with mobile pipeline is presented here. The detailed analysis is carried out for Finland. The methodology is applicable also for other Nordic countries.

On July 14, 2021, the European Commission published a proposal «Fit for 55» package with actions for different sectors[6]. As a part of this package, the Alternative fuel infrastructure directive (AFID) is proposed to be changed so that the following is obligatory:

"Hydrogen refuelling stations:

- *will be made available every 150 km by 2030 along the TEN-T core network;*
- *in every urban node serving both light duty and heavy duty vehicles by 2030."*

Concerning Finland, this would mean absolute minimum about 10 HRSs. With 20 HRS (national non-binding target) almost all the main heavy-duty traffic routes in Finland could be covered, assuming 150 km distance between HRS. It can be estimated that about 50 HRS would cover all relevant heavy-duty traffic routes in Finland.

In this case study, the work will be limited to the AFID requirement proposed July 14, 2021. Contrary to the AFID proposal, the calculation is done assuming 350 bar pressure level with 1 tonne capacity per day, not 700 bar. It is still unclear which will be the dominating pressure level, or if liquified hydrogen (LH_2) is dominating already by 2030. In Finland, the use of 700 bar in heavy-duty trucks would make no sense, compared to 350 bar, as volume is typically not the limiting factor for heavy-duty truck capacity, due to vehicle dimensions in Finland.

The core network and comprehensive traffic network in Finland is illustrated in *Figure 5*. According to the proposed AFID changes, locations of the new 13 HRSs are added to the map. The locations are selected so that these are the same as existing refuelling station locations for heavy-duty traffic operated by Neste Oyj.

In Finland, it seems to be that all these HRSs could be filled by mobile pipeline in the radius of <300 km from two locations: Porvoo and Oulu. Therefore, the locations of industrial electrolysers are selected for Porvoo (Neste refinery) and Taka-Laanila industrial area in Oulu, where existing large-scale hydrogen production from liquefied natural gas (LNG) could be replaced by water electrolysis.

[6] https://www.consilium.europa.eu/en/policies/green-deal/eu-plan-for-a-green-transition/

		Neste Oyj Porvoon jalostamo,			Kemira Oulu, Typpitie,		
	Name and address	km	avg	h	km	avg	h
1	Neste Truck Naantali Luolala Viestitie 1 , 21100 NAANTALI	215	76,7	2,8	628	71,5	7,5
2	Neste Truck Turku Satama Tuontiväylä Tuontiväylä , 20200 TURKU	206	77,3	2,7	626	71,7	7,4
3	Neste Truck Vihti Myllylampi Hiidenmäentie 268 , 03100 VIHTI	82	73,4	1,1	624	72,7	7,3
4	Neste Truck Helsinki Vuosaari Rahtarinkatu 4 , 00980	32	65,3	0,5	601	77,4	6,6
5	Neste Truck Mäntsälä Tuuliruusu Lahden moottoritie 1150 ,	53	64,4	0,8	553	76,6	6,1
6	Neste Truck Hartola Yhdystie Yhdystie 2 , 19600 HARTOLA	171	80,0	2,1	428	74,0	4,9
7	Neste Truck Jyväskylä Kirri Kirrintie 2 , 40270 JYVÄSKYLÄ	266	77,5	3,4	333	73,5	3,9
8	Neste Truck Pihtipudas Rupontie 3 , 44800 PIHTIPUDAS	391	75,0	5,2	207	75,4	2,3
9	Neste Truck Kärsämäki Paanulinna Haapajärventie 1 , 86710	472	75,2	6,3	127	74,4	1,5
10	Neste Truck Oulu Logistiikkakeskus Terminaalitie 1 , 90400 OULU	596	75,2	7,9	9	51,0	0,2
11	Neste Truck Keminmaa Teollisuuskyläntie Teollisuuskylänraitti 15 ,	710	74,8	9,5	112	68,8	1,4
12	Neste Truck Loviisa Ankkurituuli Länsikaari 3 , 07900 LOVIISA	52	75,8	0,7	583	73,6	6,7
13	Neste Truck Kotka Mussalo Merituulentie, Mussalon portti , 48400 KOTKA	98	74,6	1,3	587	73,2	6,8

Figure 5. The core network and comprehensive traffic network in Finland[7]. Numbered circles indicate potential locations for the HRSs. Filled green dots illustrate the possible locations for semi-centralised hydrogen production facilities in Porvoo and Oulu[8].

Selected potential HRS locations were analysed in terms of hydrogen transportation costs. As shown in *Figure* 6, the transportation cost varies between 0.7 €/kg and 1.2 €/kg of hydrogen depending on the transportation distance. The average cost for the transportation in Finland is 0.9 €/kg of hydrogen.

In deliverable D2.4 of the Next Wave project, different options for hydrogen transport containers were studied. In a 45 ft single container configuration, transport of 1,200 kg of hydrogen is possible if a pressure level of 500 bar is applied.

When hydrogen is transported to the HRS, the selected pressure level is 500 bar (this is also the pressure level used in the HDT study (FCH-JU 2020)). The use of 500 bar will become common in Europe. It is also assumed that a common type of container solution (500 bar, 40 ft) will be used, even if further optimisation based on national vehicle dimensions could be applied.

[7] https://vayla.fi/en/transport-network/transport-system/ten-t

[8] This Figure and Figures 9-12 are created using interactive map services in https://vayla.fi, which contain open data by National Land Survey of Finland licensed under a Creative Commons Attribution 4.0 International License.

Therefore, the transportation cost is based on the 68 tonnes ADR transport using a B-train (also B-link) configuration. In this configuration, two 40 ft hydrogen containers at 500 bar can be transported and corresponding hydrogen weight (net) is assumed to be 1,100 kg per container.

When hydrogen is produced on-site, then as a backup storage solution, 40 ft UAC high cube containers (200 bar) or similar are assumed. The size of the backup storage is dimensioned for a 1-day consumption, with a maximum configuration of two storage containers. This adds CAPEX for station solution.

The assumption is that the daily use of hydrogen at the station is significant by 2030. The values from HDT study are used with an addition of booster compressor for in-situ production.

If the net payload of hydrogen is reduced from 1,500 kg/truck to 1,000 kg/truck, the transportation costs increase as illustrated in *Figure 7*. Due to the assumption that the driver will do both the loading and unloading of the container at each side (1 h each), the total driving time for one direction can be 3.5 h, hence 260 km (assuming 75 km/h speed).

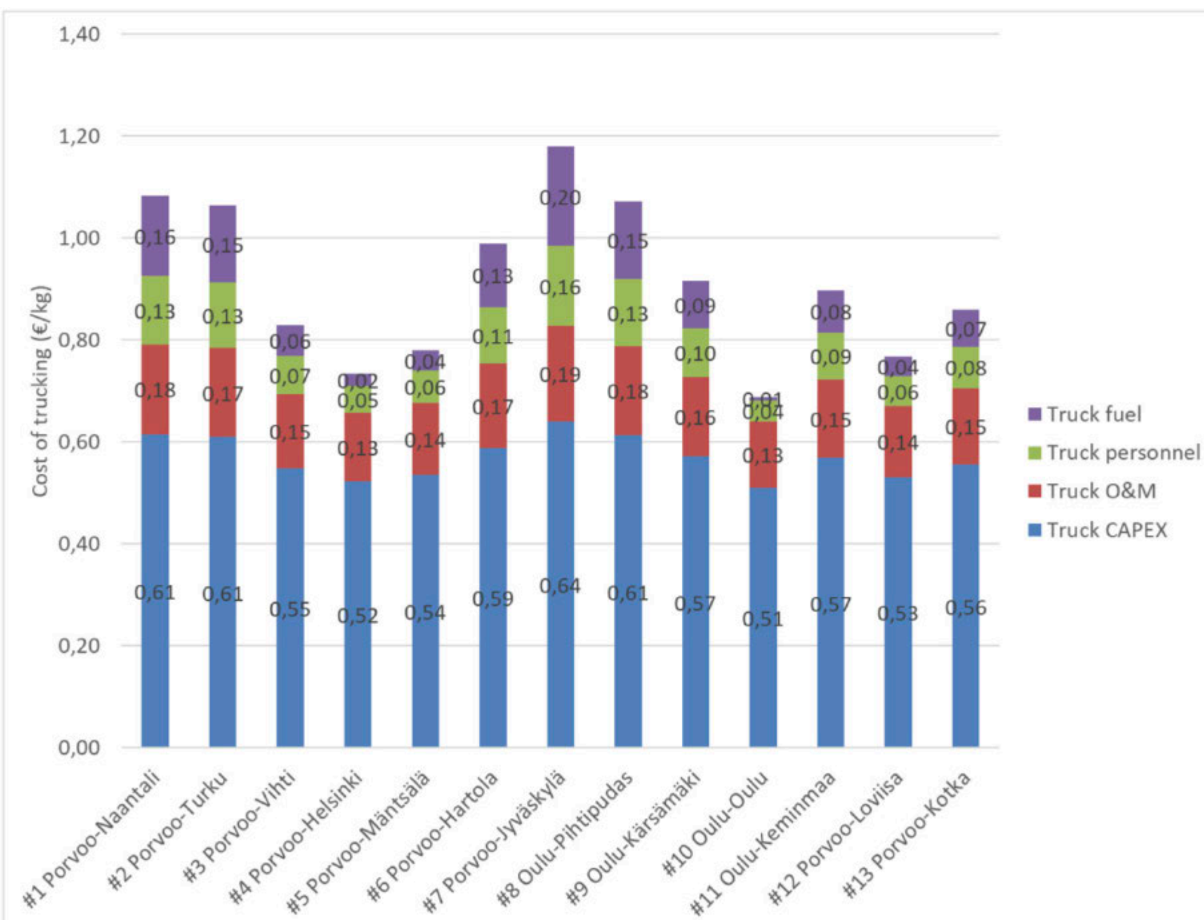


Figure 6. Trucking cost for hydrogen in Finland for selected routes. Each station processes 1,000 kg/day. Hydrogen payload 1,500 kg/truck. Truck CAPEX includes hydrogen containers.

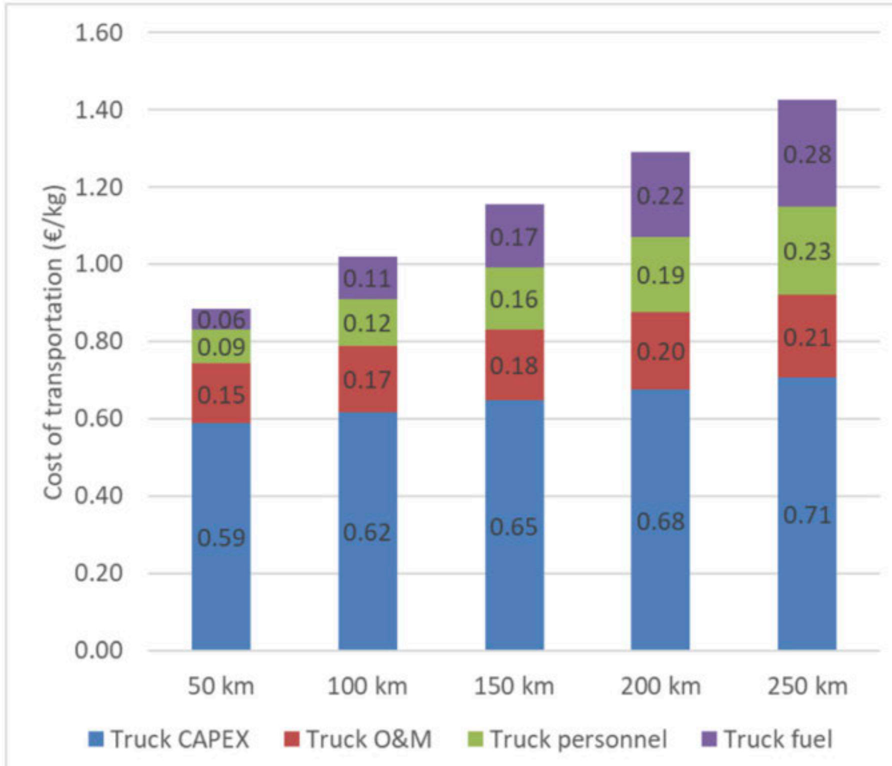


Figure 7. Transportation cost of hydrogen to a HRS at various distances processing 1,000 kg/day. Hydrogen payload 1,000 kg/truck. Speed of the truck 75 km/h. Truck CAPEX includes hydrogen containers.

The total distribution cost

The total specific delivery cost of hydrogen (SC_{total}, € kg^{-1}) is divided into hydrogen production ($SC_{production}$), processing ($SC_{processing}$), trucking ($SC_{trucking}$), and dispensing ($SC_{dispensing}$) costs, *Eq. 12*:

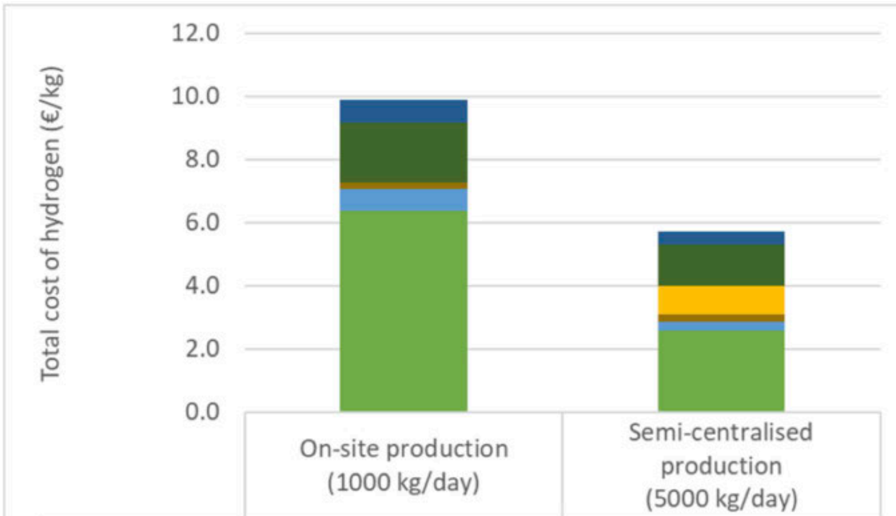
$$SC_{total}\ (€\ kg^{-1}) = SC_{production} + SC_{processing} + SC_{trucking} + SC_{dispensing} \quad \textit{Eq. 12}$$

Hydrogen processing costs ($SC_{processing}$) includes compressor costs (SC_{comp}) and other costs (SC_{site}). Equations used to calculate each cost component are presented in the previous chapters.

For on-site electrolysis, a 40% utilisation rate is assumed as well as 50 €/MWh electricity price. In the semi-centralised case, an 80% utilisation rate is assumed and 30 €/MWh electricity price. If the price of the electricity increases by 10 €/MWh, the cost of hydrogen increases by 0.5 €/kg.

The mid-storage of hydrogen is assumed to be at 200 bar and the cost of the storage 400 €/kg. The specific cost of the mid-storage to the hydrogen is highly dependent on the storage capacity. For this specific case, it is assumed that the mid-storage is for 1-day usage. The mid-storage cost for hydrogen is calculated by using the *Eq. 2* and *Eq. 3*, and an operation costs of 4%. Due to the fact that the gaseous hydrogen storage prices do not benefit from the scale, the cost is the same for both electrolyser options.

The dispensing cost of the hydrogen was calculated by using the HDRSAM model. For on-site electrolysis, a 20 bar suction pressure was used, while in the semi-centralised case, a suction pressure of 500 bar was used.

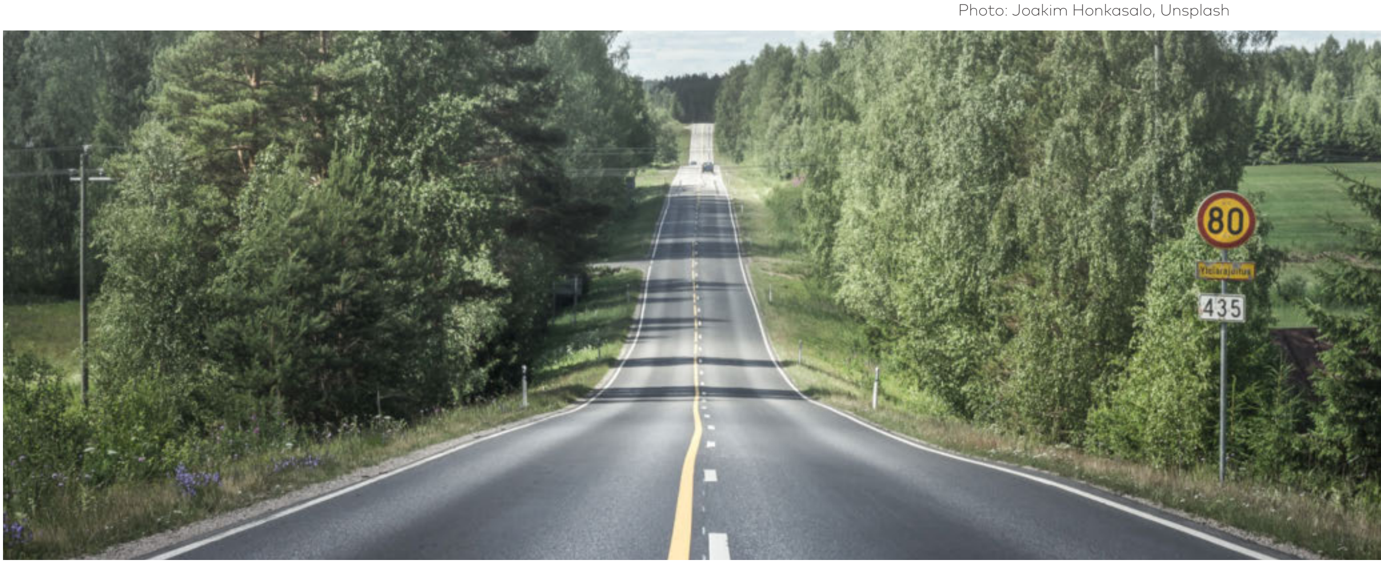


	On-site production (1000 kg/day)	Semi-centralised production (5000 kg/day)
Margin	0.7	0.4
Dispensing	1.9	1.3
Transportation	0.0	0.9
Mid-storage	0.2	0.2
Processing	0.7	0.3
Production	6.4	2.6

Figure 8. Total cost of hydrogen for heavy-duty trucks (350 bar) considering on-site production (1,000 kg/day at 50 €/MWh) and semi-centralised production (5,000 kg/day at 30 €/MWh) of hydrogen. If the price of electricity increases by 10 €/MWh, the cost of hydrogen increases by 0.5 €/kg.

One realistic addition to the model is to assume, that the produced heat has a value of e.g., 30 €/MWh. If 80% of the heat can be utilised, the levelized cost of hydrogen can be decreased by 0.5 €/kg. This would conclude to a total price of 9.4 €/kg and 5.2 €/kg for on-site and semi-centralised production, respectively.

Photo: Joakim Honkasalo, Unsplash



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Appendices

Methodology for calculating the number of trucks and trailers required

The number of required deliveries per day will depend on the hydrogen demand and the payload of the truck:

$$required\ deliveries\ per\ day\ (day^{-1}) = \frac{Hydrogen\ demand\ (kg\ day^{-1})}{Net\ hydrogen\ payload\ (kg)}$$

Total trip time will depend on unloading/loading (drop-off/pickup) times, transport distance and average speed according to:

$$total\ trip\ time\ (h) = \frac{2 \times one - way\ distance\ (km)}{average\ driving\ speed\ (km\ h^{-1})} + loading\ time\ (h) + unloading\ time\ (h)$$

Theoretical maximum number of trips for each truck per day can then be calculated:

$$max\ \#\ of\ trips\ per\ day\ per\ truck\ (day^{-1} truck^{-1}) = \frac{24h}{total\ trip\ time\ (h)}$$

Required number of trucks was calculated using the required number of deliveries to meet the demand and the theoretical maximum number of trips each truck can make in one day by also considering the availability of trucks:

$$required\ \#\ of\ trucks = \frac{required\ trips\ per\ day}{max\ \#\ of\ \ trips\ per\ day\ per\ truck * truck\ availability\ (\%)}$$

This number was rounded up to nearest larger integer. After rounding up, the lowest number of trips per day per truck that meets the hydrogen demand allowing also non-integer numbers is used in the analysis. For instance, 0.5 trips per day per truck could mean delivery every other day.

The number of trailers needed for gaseous / compressed hydrogen (GH_2) delivery options is three times the number of trucks: one is being transported, one is being filled up at the hydrogen source and one is being emptied at the hydrogen consumer. The trailers act as storages and thus no additional storages are needed. In case of hydrogen transport by means of liquid organic hydrogen carriers (LOHC), the trucks will wait while the tanker trailer is first unloaded and then loaded. Thus, storage tanks are required for LOHC base delivery. Storages were considered part of the hydrogen processing costs.

Methodology for calculating trucking costs

The annualized investment costs for truck fleets ($IC_{ann,trucking}$) where calculated by considering the required number of trucks and trailers and their investment costs (IC) and capital recovery factors (CRF):

$$IC_{ann,trucking} = (\#\ of\ trucks) \times CRF_{truck} \times IC_{truck} + (\#\ of\ trailers) \times CRF_{trailer} \times IC_{trailer}$$

Operation and maintenance costs (in €/kg H_2) were calculated from the specified variable (VC) and fixed costs (FC) of the trucks and trailers:

$$SC_{trucking,O\&M} = \frac{(\#\ of\ trucks) \times VC_{truck} \times (annual\ drive\ distance) + (\#\ of\ trailers) \times (IC_{trailer} \times FC_{trailer})}{Delivered\ useful\ hydrogen\ per\ year}$$

Personnel cost for each kg of hydrogen delivered depends on the total trip time, hourly salary of the driver, and delivered amount of useable hydrogen per truck:

$$SC_{trucking,personnel} = \frac{(total\ trip\ time) \times (hourly\ salary)}{Delivered\ useable\ hydrogen\ per\ truck}$$

The specific delivery costs due to fuel consumption of truck can be calculated from drive distance, fuel consumption, fuel price, and delivered amount of useable hydrogen:

$$SC_{trucking,fuel} = \frac{2 \times (one-way\ distance) \times FuelConsumption \times FuelPrice}{Delivered\ useable\ hydrogen\ per\ truck}$$

The total specific hydrogen delivery cost from trucking then becomes:

$$SC_{trucking} = \frac{IC_{trucking} \times CRF_{trucking}}{Delivered\ useful\ hydrogen\ per\ year} + SC_{trucking,O\&M} + SC_{trucking,Fuel} + SC_{trucking,personnel}$$

Hydrogen demand for HRS in Finland

There are several interesting areas of concentrated heavy-duty traffic in Finland, *Figure 9* (left), which is to be combined with the main locations for industrial hydrogen production and use, *Figure 9* (right). The maps and heavy-duty transportation volumes (vehicle pass per day) in *Figure 9* are retrieved from the public database[9].

[9] https://vayla.fi/vaylista/aineistot/kartat/liikennemaarakartat

More details of transportation volumes of Finland for different industry segments have been collected and illustrated by WSP in two publications[10]. WSP has illustrated the total transportation volume as well as transportation volumes for different industry segments.

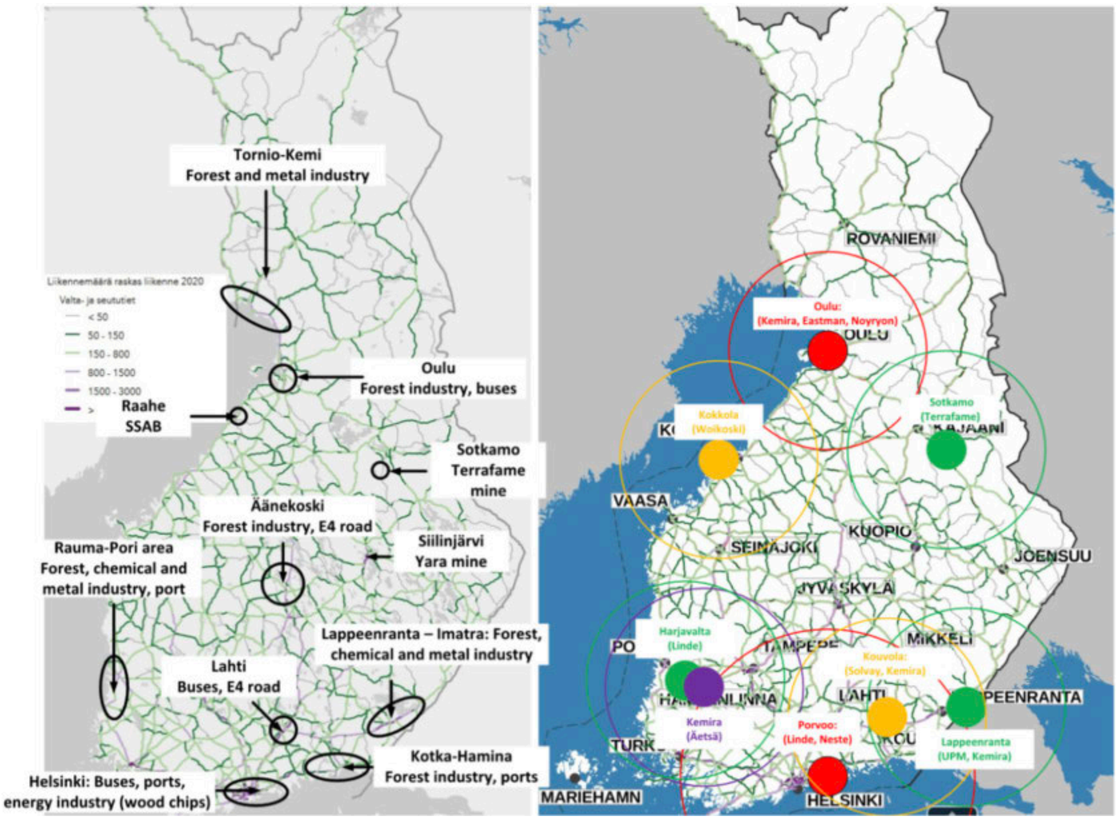

Figure 9. Heavy-duty traffic hotspots in Finland (left) and hydrogen production sites (right).

The heavy-duty traffic figures have been collected from Environmental permits as well as permit applications. These are compared with heavy-duty transportation volumes available from Väylävirasto.

A further analysis has been performed for the ports and industry of four main areas:

- Kemi-Tornio-Oulu area in the north.
- Helsinki-Porvoo area with focus on Vuosaari port and Neste refinery.
- South-East Finland (Imatra-Lappeenranta-Kouvola and Kotka-Hamina). This include both industry areas as well as Kotka-Hamina ports.

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10 Elinkeinoelämän kuljetukset tieverkolla -volyymi-ja arvoanalyysi, WSP Finland (2017)
https://julkaisut.vayla.fi/pdf8/lr_2017_elinkeinoelaman_kuljetukset_web.pdf
WSP Finland Oy 2017
https://www.sttk.fi/wp-content/uploads/sites/2/2017/03/Liikenteen-infrastruktuuri-tulevaisuuden-mahdollistajana.pdf

Kemi-Tornio-Oulu case

In the northern Finland, a very interesting case for industrial transport is Kemi-Tornio area combined with Oulu, *Figure 10* and *Table 4*. Transport from the Outokumpu Tornio stainless steel factory and Outokumpu Keminmaa mine as well as Stora Enso and Metsä fibre factories in Kemi form a large, concentrated use of heavy traffic, which would also support E4 road. In Oulu, there is a major port, industry CHP plants and city buses.

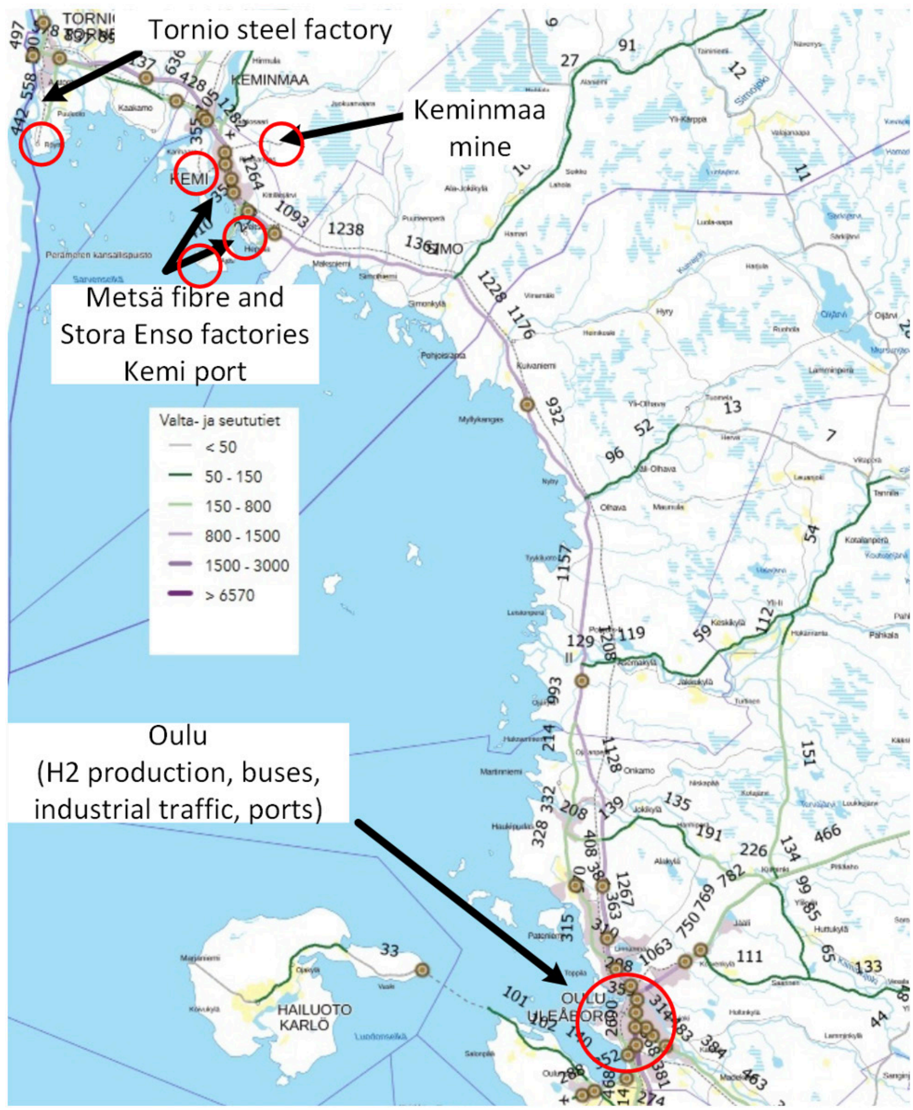

Figure 10. Hotspots of heavy-duty traffic in Kemi-Tornio-Oulu area.

Concerning the Kemi-Tornio-Oulu area, the transport of chromium oxide ore from the mine to the steel factory could possibly be done using battery vehicles, due to very regular traffic. Also the transport of raw wood and goods from Kemi port to the Stora Enso and Metsä fibre factories could possibly be done using battery electric trucks, due to short distance.

The distance from the Kemi/Tornio to the closest semi-centralised industrial hydrogen production place (Oulu) would be just above 100 km. Therefore, hydrogen could be transported from Oulu as an alternative to local production.

In Oulu area, the location of electrolyser for the transportation needs could be in the Laanila industry area, where it would provide hydrogen and oxygen for hydrogen peroxide production.

Table 4. Potential hydrogen consumption sites in Kemi-Tornio-Oulu area (external road traffic and internal traffic)

Site / City	External truck visits	Internal	Environmental permit Dnro or other reference
Kemi Outokumpu mine	85 truck loads from mine to Tornio (80 km)	17 kt CO_2 emissions (mine)	Outokumpu Chrome Oy Kemi mine expansion EIA document[11]
Tornio (Outokumpu steel)	220 truck loads per day when traffic from mine is excluded	3,1 milj. tonnes internal traffic	Outokumpu Chrome Oy Sulatto EIA plan[12]
Hydrogen need: about 5-10 tonnes per day (single HRS is enough, if not for internal use)			
Kemi Stora Enso	140-160 long distance truck loads per day	100 truck loads per day	Psy-2004-y-193 and Dnro PSAVI/2599/2015
Kemi Metsä fibre	150 loads per day (now) to 350 (long and short)	-	PSAVI/7988/2019
Hydrogen need: about 5-10 tonnes per day (2 HRS needed)			
Oulu Stora Enso	300 loads per day	-	PSAVI/2638/2019
Oulu ports (Oritkari, Nuottasaari, Vihreäsaari and Toppila)	1000 loads per day	200-300 kg-H_2/day for internal logistics	Psy-2003-y-128
Oulu Laanila all industry	130 loads per day		PSAVI/1144/2020
Oulu, Oulun Energia Toppila	100 loads per day		Dnro PSAVI/1872/2014
Hydrogen need: 30-50 tonnes per day (3-5 HRS)			

Imatra-Joutseno-Lappeenranta-Kouvola-Kotka-Hamina case

The traffic volume of Finnish forest industry is shown in *Figure 11* with the location of major hydrogen production points as well as potential consumption points, listed in *Table 5* and in *Table 6*.

Imatra and Lappeenranta are located 15-25 km from Joutseno (Lappeenranta), where Kemira is producing 12,000 tonnes of hydrogen as a by-product. About 2,000 tonnes of this is from chlor-alkali production, and probably suitable for traffic use without major purification effort.

11 https://www.ymparisto.fi/fi-fi/Asiointi_luvat_ja_ymparistovaikutusten_arviointi/Ymparistovaikutusten_arviointi/YVAhankkeet/Outokumpu_Chrome_Oyn_Kemin_kaivoksen_laajentaminen_Keminmaa

12 https://www.ymparisto.fi/fi-fi/Asiointi_luvat_ja_ymparistovaikutusten_arviointi/Ymparistovaikutusten_arviointi/YVAhankkeet/Outokumpu_Chrome_Oy_sulatto_Tornio

In Lappeenranta, UPM biofuels is producing Bioverno and uses currently 7,800 tonnes of hydrogen with expansion plans to the future maximum use would be 10,800 tonnes/year.

Kouvola is located a bit further away (100 km from Lappeenranta), but still in the same area. In Kouvola, there is a hydrogen peroxide production plant (Solvay chemicals) as well as by-product from Kemira factory.

Kotka-Hamina port as well as industry in these cities is also located only 130 km away from Joutseno and 70 km from Kouvola. In Kotka, Dansico is an existing minor consumer of hydrogen.

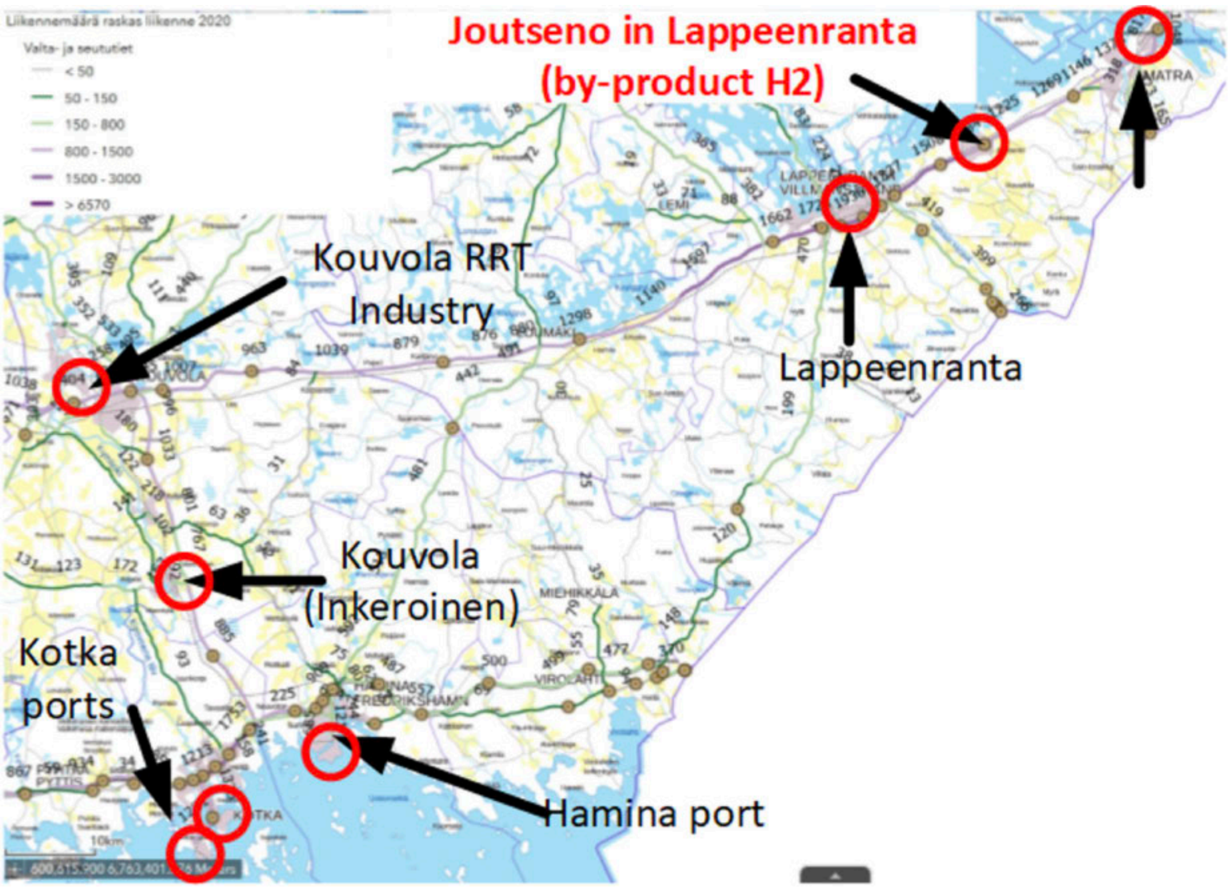

Figure 11. Hotspots of heavy-duty traffic in south-east Finland.

A major part of the traffic in *Figure 11* is forest industry traffic from the factories to the ports of Kotka and Hamina. In addition to forest industry and ports, there are also other industries with major transportation needs in the area, *Table 5* and in *Table 6*.

All in all, south-east Finland is one of the most suitable larger markets for heavy-duty trucks, and the application with the largest potential may be forest industry product transport to the ports and between the factories.

Table 5: Potential hydrogen consumption sites in Imatra-Joutseno - Lappeenranta (–Kouvola) (external road traffic and internal traffic)

Site / City	External truck visits	Internal	Environmental permit Dnro or other reference
Imatra, Ovako	50 truck visits per day		ESAVI/346/04.08/2013
Imatra Stora Enso	340 truck visits per day		ISY-2004-Y-170
H2 need for external traffic: 10-15 tonnes per day (2 HRS)			
Lappeenranta (Joutseno), Kemira factory	15 long distance truck loads per day and 10 short	-	ESAVI/11436/2016
Lappeenranta (Joutseno), Metsä Fibre Oy, Metsä Board and Stora Enso Wood products	Total 350-400 for all three factories		ESAVI/2046/2015 ESAVI/2043/2015 ISY-2004-Y-240
H2 need for external traffic: 10-15 tonnes per day (2 HRS)			
Lappeenranta, UPM	250-300 truck visits per day	Reach stackers, trucks	ISY-2004-Y-71 ESAVI/167/04.08/2011
Lappeenranta, Nordkalk	45 truck visits per day	200 loads	ESAVI/3/04.08/2014
Lappeenranta, Fazer makeiset	20 truck visits per day		LPR/365/11.01.00.00/2018
Lappeenranta, Kaukaan voima	50 truck visits per day		ISY-2006-Y-241
H2 need for external traffic: 15-20 tonnes per day (2-4 HRS)			
Kouvola (Inkeroinen), Stora Enso	100 truck visits per day	572 m3 diesel per year	Dnro ESAVI/8648/2016 Dnro ESAVI/2466/2016
H2 need for external traffic: less than 5 tonnes per day			
Kouvola, UPM Kymin tehtaat	100-200 truck visits per day		ESAVI/1834/2016
Kouvola, Solvay Chemicals	20 truck visits per day		ESAVI/9201/2014
Kouvola, Road and railway terminal (RRT)[13]	Not known (total volume 250,000 TEU containers)		
H2 need for external traffic: 5-10 tonnes per day (2-3 HRS)			

13 https://www.kouvola.fi/kouvolankaupunki/strategia/karkihankkeet/rautatie-ja-maantieterminaali-kouvola-rrt/

Photo: Roberto Hanas, Unsplash

Table 6: Potential hydrogen consumption sites in Kotka and Hamina area (external road traffic and internal traffic)

Site / City	External truck visits	Internal	Environmental permit Dnro or other reference
Hamina, Hamina port	230 trucks per day		ESAVI/289/04.08/2013
Hamina, Fintoil	15 trucks per day		ESAVI/13144/2020
H2 need for external traffic: 5-10 tonnes per day (1 HRS)			
Kotka smaller ports (Hietanen, Kantasatama, Sunila and ja Halla)	Total 800 trucks per day		ESAVI/290/04.08/2013
Kotka Mussalo ports	1200 trucks per day	TBD	ESAVI/288/04.08/2013
Kotka Kotkamills	280		ESAVI/10733/2015
Kotka Stora Enso	110-140		ESAVI/846/2016
H2 need for external traffic: 40-80 tonnes per day (2-8 HRS)			

Helsinki-Porvoo case

Helsinki area is the only area in Finland where bus traffic would be sufficiently large to support own hydrogen production for hydrogen fuel cell (FC) buses. However, the total amount of FC buses will depend on the cost-efficiency of the FC buses compared to battery electric buses, which have been developing rapidly during last two years.

The total number of buses will be about 1,300-1,500 in the future, and if only even 20% of them are FC buses this will create a demand for up to 10 tonnes hydrogen per day.

In Helsinki area, there are roads with more than 4,000 heavy vehicles passes per day, as seen in *Figure 12*. Ten-T core network is also crossing Helsinki area starting from Vuosaari port (illustrated with yellow lines and arrows). Therefore, the eastern Helsinki area would be a natural place to start the HRS infrastructure rollout in Finland.

There are also very large, concentrated heavy-duty transportation needs in Helsinki area. One of the main points for heavy-duty transportation is in Eastern Helsinki, Vuosaari port as well as Helen Vuosaari bioheat plant. These are illustrated in *Figure 12* as well as major logistics centres, which are in three main locations (Pasila, airport area, Kerava-Sipoo). The potential hydrogen consumption sites in Helsinki / Vuosaari are listed in *Table 7*.

Figure 12: Locations of Vuosaari Port, Vuosaari bioheat plant and future bus depos in Helsinki area[14].

In addition to Vuosaari port, there are two major ports in Helsinki; Länsisatama and Etelä-Satama. The future of these ports is under discussion. However, the cargo transported through these ports (totally, about 3 million tonnes) is in trucks and there are no container or bulk cargo handling in these ports. Therefore, these ports are not included in this analysis.

Table 7: Potential hydrogen consumption sites in Helsinki / Vuosaari (external road traffic and internal traffic)

Site / City	External (visits, includes back and forth)	Internal	Reference
Helsinki, Helen Vuosaari bioheat plant	75 truck visits when operating at full power		ESAVI/2015/2018
Helsinki, Vuosaari Port	1180 truck visits per day		ESAVI/306/04.08/2012
H2 need for external traffic: 20-40 tonnes per day (2 HRS)			
Porvoo, Neste Oil	200-250		ESAVI/284/04.08/2013 ESAVI/1713/2016
H2 need for external traffic: 5-10 tonnes per day (one HRS)			

[14] Viittaa varikkoselivtys

City bus traffic in selected cities

The use of hydrogen in city buses can support the hydrogen use in heavy-duty truck traffic and vice versa. Therefore, the main cities with large amount of city buses are also collected.

Excluding Helsinki area, all other cities would need support of heavy-duty truck traffic. Therefore, it is not the largest bus fleets that are the most attractive, but the largest combination fleets as well as possible industrial hydrogen production.

The most promising cities for FC buses, in addition to Helsinki area, could be Tampere, Turku, Oulu, Lahti, Lappeenranta, Kouvola, and Kotka. Figures for buses and line-kilometres are collected in *Table 8*.

A more detailed analysis should be carried out how large could be the synergies when hydrogen heavy-duty trucks and hydrogen buses are operated in the same area. The additional time needed, when the same HRS is used may be significant and be larger the savings due to lower hydrogen cost.

Table 8. The number of city buses and line km in selected cities

City/area	Buses	Line-km (million)
Helsinki area	1304	93
Tampere	~ 100	8.8
Turku	~ 100	10
Oulu	~ 100	10
Lahti	~ 80	8
Kuopio	~ 55	5.56
Jyväskylä	50-60	5-6
Lappeenranta	~ 20	1.7
Kouvola	~ 10-20	1-2
Imatra	5	0.6
Kotka	20	2
Pori	30	2.75
Porvoo area	-	1.36
Järvenpää	-	0.426
Hämeenlinna	-	0.8
Hyvinkää	-	0.5
Riihimäki	-	0.5

All in all, the cities in *Table 8* cover more than 70% of the total city bus transport in Finland.

The assumed hydrogen consumption is 8-10 kg per 100 km and total km are 1.1 times line-km. The smallest sensible fleet size is 20 buses (500 kg H_2/day), when hydrogen is delivered in semi-centralised way and the main consumer of hydrogen is a bus fleet.

Photo: Elijah O'Donnell, Pexels

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