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Hydrogen and heavy trucks in Gävleborg

Peder Zandén Kjellén

UNIVERSITY OF GÄVLE

The following corrections have been made in the second version of the report.

Location	Error	Correction
Page 10	The literature regarding production cost for renewable hydrogen varies widely. PEM electrolyzers coupled with wind power alone, differ between 1.7–7.9 EUR/kg H2. If other production methods and energy sources are included, the spread increases to 1–19.5 EUR/ kg H2 (Ball, Basile, & Veziroglu, 2016; Dincer & Acar, 2014; El-Emam & Özcan, 2019; Sapountzi et al., 2017).	The literature regarding production cost for renewable hydrogen varies widely. PEM electrolyzers coupled with wind power alone, differ between 4.5 –7.9 EUR/kg H2. If other production methods and energy sources are included, the spread increases to 1–19.5 EUR/ kg H2 (Ball, Basile, & Veziroglu, 2016; El-Emam & Özcan, 2019).

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Hydrogen and heavy trucks in Gävleborg

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Abstract

In 2018, 18% of global greenhouse gas (GHG) emissions arose from road transportation. In Sweden, however, 32% of total greenhouse gas emissions originated from transportation and the Swedish government has committed to reductions of 70% for domestic transportation (excluding aviation) by 2030 compared to 2010 levels. As the globalization trend continues, the transportation of goods, and resulting emissions, is expected to sharply increase in the years to come. At the same time the need to reduce GHG emissions is clear. The UN climate agreement has been signed by 195 countries, with the goal to maintain the global temperature increase below 2°C. However, scientists and experts warn that current efforts are not enough.

An increasingly attractive alternative for freight transport is the hydrogen powered, fuel cell electric truck (FCET). Fuel cells generate electricity which, coupled with a battery, drives an electric motor. Like a battery-powered electric vehicle (BEV), the FCET has zero tailpipe emissions. The battery is used to stabilize power output and is charged either with the fuel cells or by taking advantage of regenerative braking, a concept of converting kinetic energy to electricity while deaccelerating (braking). Tank-to-wheel (TTW) fuel cell efficiency is around 55%. The fuel cell system occupies less space and weighs less than the battery electric counterpart.

The purpose of this study is to support regional actors interested in taking steps towards a hydrogen-based economy by investigating the feasibility of hydrogen as a fuel for goods transportation in Gävleborg. Specifically the study looks at trucks above 32 tonnes, with a transportation route to the Port of Gävle. To assist this purpose the following research questions are addressed:

- Which electricity-based production methods are viable options for supplying Gävleborg with low emission hydrogen fuel?
- How can regional electrolyzers create benefits and promote the buildout of hydrogen supply infrastructure?
- To what extent is it possible for regional road freight companies to use fuel cell electric vehicle trucks today and in the future?
- What is the potential environmental impact of replacing a share of conventional trucks with fuel cell electric vehicle trucks transporting goods to and from the Port of Gävle?

Although still associated with high costs, around 25% more expensive than a diesel counterpart, it is predicted that FCETs can be cost competitive, from a total cost of ownership perspective, as soon as 2027. The Hyundai Xcient, the first type-built FCET in Europe, has a range of 400 km and a gross combination weight (GCW) of 36 tonnes. In Sweden, 70% of all road based goods, based on weight, are transported on trucks with GCW above 55 tonnes, and trucks can typically travel around 1,000 km on a single tank. Although not expected to be available until 2024 in the US, Nikola Motor Co. boasts that their flagship Nikola Two will offer a range of over 1,000 km and a refueling time of less than 15 minutes. However, it will still only have a GCW of 36 tonnes.

Sandviken in Gävleborg has one of only four operational hydrogen refueling stations (HRS) in Sweden. In Hofors, Ovako plans to build one of the world's largest electrolyzers for their own steel production[1]. The Port of Gävle is also looking to build an electrolyzer with an accompanying HRS. In Borlänge, Maserfrakt has received funding to build an HRS. These locations are strategically important as much of the heavy goods transport in Gävleborg and Dalarna travels along E16 and to the harbor in Gävle. Existing and planned HRS could support around 50 FCETs.

The most common hydrogen production pathway today is by using natural gas. This leads to excessive emissions and for FCETs to be sustainable it is crucial that the hydrogen is produced from

[1] While in 2021/2022 it will be one of the largest at 17 MW, companies globally have announced plans for 100 MW electrolyzers, overshadowing existing projects.

renewable sources. The technology expected to produce the bulk of renewable (green) hydrogen globally is electrolysis. Electrolysis is a process of applying electricity to water, splitting the water molecules to produce hydrogen and oxygen gas, and heat.

There are four main electrolysis technologies: alkaline electrolysis, proton exchange membrane (PEM), anion exchange membrane (AEM), and solid oxide electrolysis cells (SOEC). Details of each technology are outlined in S1.

S1. The four main electrolysis methods, state-of-the-art key performance indicators

Electrolysis	Alkaline	PEM	AEM	SOEC
Temperature	50–80°C	70–90°C	40–60°C	700–850°C
Electrolyte	liquid	solid (polymeric)	solid (polymeric)	solid (ceramic)
Voltage Efficiency (Low heating value)	50–68%	50–68%	52–67%	75–85%
Hydrogen efficiency	50–78 kWh/kg H_2	50–83 kWh/kg H_2	57–69 kWh/kg H_2	40–50 kWh/kg H_2
Stack lifetime	60,000 h	50,000 – 80,000 h	> 5,000 h	< 20,000 h
Maturity	Commercial	Early commercial	Research	Research
Advantages	• Mature technology • Long-term stability • Low capital costs • Non-noble materials	• High current density • Simple design • Compact design • Dynamic operation • Fast response • Reversible process	• Non-noble materials • Non-corrosive electrolyte • Compact design • Low capital cost • No leakage	• High energy efficiency • Non-noble materials • Low capital cost • Reversible process • Co-electrolysis possible
Disadvantages	• Bulky design • Low current density • Corrosive electrolyte • Non-dynamic operation • Gas permeation	• High membrane cost • Noble materials • Acidic environment	• Low current density • Membrane degradation • Large voltage drop	• Bulky design • Unstable electrodes • Sealing problems • Brittle ceramics
Intermittent power compatibility	Low	High	High	Low

While the price of hydrogen varies widely in the literature, everyone seems to agree that the price of green hydrogen currently comes at a high cost. The costs can roughly be divided into two categories, the electrolyzer and the electricity. The cost of electrolyzers is expected to fall rapidly as total installed capacity goes from 0.07 GW in 2019 to 6 GW in 2025 and 25 GW in 2030. The most cost-effective technology is alkaline, but PEM will likely be the dominant technology as it matures. Sweden is one of the countries with the largest potential to produce cheap hydrogen. As much as 80% of production costs can stem from electricity and Sweden has one of the lowest electricity prices globally. It could even be possible to produce hydrogen below EUR 3/kg in 2025, improving the business case for FCETs significantly.

A way of reducing the production cost of hydrogen is to utilize the by-products, oxygen and heat. The location of the electrolyzer will therefore be important to improve profitability. The steel industry is a large consumer of oxygen, but another interesting new alternative could be on-land fish farms, which require large amounts of oxygen but can also utilize the low grade heat of electrolysis.

Electrolyzers can also help support a regional buildout of wind and solar power. It is expected that wind generation will have to increase to around 80 TWh, or a fourfold increase since 2019, until 2040 if Swedish electricity needs and targets are to be met. Electrolyzers and particularly PEM are suitable for varying load and can act as a supplement to RES to improve capacity factors and participate in grid balancing markets to help maintain a stable electricity grid. One reason for low capacity factors of renewables are grid congestion; power lines are simply too thin to transport electricity from where it is produced to where it is used. Swedish socio-economic cost could already amount to EUR 8 billion per year due to a lack of power availability. Even Gävle is affected. A buildout of hydrogen electrolyzers can complement renewable power and could be important to maintain regional attractiveness for new companies and existing ones looking to expand. When Microsoft chose Sandviken and Gävle as site locations for their data centers, access to RES was a deciding factor. To continue to attract foreign investment in the area, a buildout of the regional energy supply is essential.

One of the driving factors for FCETs is the reduced environmental impact they have compared to diesel. Assessing environmental impact from the production of vehicles is difficult. There is a lack of standardization in vehicle life cycle assessments. Access to environmental impact data for fuel cell electric vehicles and FCETs is limited and is in large part based on simulations, rather than real world data. Reports put life cycle GHG emissions of fuel cell systems for cars between 30 and 110 kg CO_2e/kW_{peak}. Platinum in the catalyst is one of the major contributors to GHG emissions and considerable research effort is going into reducing the amount needed for each fuel cell.

The environmental impact of hydrogen is largely dependent on the electricity mix used. While hydrogen with a Swedish electricity mix has four times lower emissions than diesel, hydrogen from wind power is almost 16 times better than diesel (S2).

S2. Comparison of well-to-wheel GHG emissions between hydrogen, diesel and HVO100

Fuel type	**g CO_2e/ tkm**
Hydrogen, Wind	3.4
HVO100	6.4
Hydrogen, Swe mix	13.2
Diesel	55.2

Considering 190 trucks travelling to the Port of Gävle every day, hydrogen produced with the Swedish electric mix can reduce tank-to-wheel emissions by about 70% from 31,000 to 9,000 tonnes CO_2e per year and would require about 3,200 tonnes of hydrogen per year. In the sample, more than 25% of the fuel was either HVO100 or RME. Replacing only biofuels, which could be the case as more progressive trucking companies are likely to already run on biofuels and are more likely to be the first to shift to FCETs, would barely reduce the emissions. The reason is that HVO100 emissions are lower than hydrogen produced with Swedish electricity mix.

Trucks with GCW above 32 tonnes are responsible for 94% of domestic payload-distance (in tonnes-km). Replacing the heavy trucks has the potential to significantly reduce road-based emissions. To do so, the price of FCETs needs to go down and payload capacity needs to increase. Most urgently, FCETs must be available to the Swedish market. Currently that is not the case and there is a risk that no trucks will be available until 2025.

It is likely that planned HRS will be in place before FCETs reach Sweden, allowing trucking companies, transporting goods along E16 and to the harbor, to get started with FCETs as soon as they are available.

Keywords: hydrogen, fuel cell, heavy duty truck, sustainable transport, electrolyzer, renewable energy

Sammanfattning

År 2018 kom 18% av de globala växthusgasutsläppen från vägtransporter. I Sverige står inrikes transporter för 32% av de territoriella utsläppen och Sverige har som mål att minska transportutsläppen med 70% till 2030, jämfört med 2010. Samtidigt som våra utsläpp av växthusgaser måste minska, förväntas behovet av transporter öka markant inom de kommande åren till följd av globaliseringen. Parisavtalet, med syftet att hålla den globala uppvärmningen under 2°C, har signerats av 195 men experter varnar för att dagens insatser inte kommer att räcka till.

Ett hållbart alternativ som är intressant för vägtransporter är vätgaslastbilar. Lastbilarna drivs med bränsleceller och ett elektriskt batteri som tillsammans driver en elektrisk motor. Vätgaslastbilarna har inga avgasutsläpp och kan ta till vara på energi som uppstår vid inbromsning och därmed höja verkningsgraden som ligger runt 55%. På grund av att bränslecellerna och vätgastankarna är mindre och lättare än motsvarande batterier, har vätgaslastbilar större lastpotential än rena ellastbilar.

Syftet med denna rapport är att stödja regionala aktörer som är intresserade av vätgas för sin verksamhet. Specifikt undersöks vätgas och dess potential för vägtransporter och lastbilar tyngre än 32 ton, med av- och pålastning i Gävle hamn. I rapporten behandlas följande frågeställningar:

- Hur kan vätgas, baserad på el, produceras med låga utsläpp i Gävleborg?
- Hur kan elektrolysörer bidra till den regionala utvecklingen och skapa infrastruktur för vätgas i Gävleborg?
- Hur är tillgängligheten och konkurrenskraften för vätgaslastbilar idag och i framtiden?
- Hur påverkas utsläppen av växthusgaser för lastbilar, som kör gods till och från Gävle hamn, om de ersätts med vätgaslastbilar?

Cirka 70% av svenska vägtransporter, räknat i godsmängd (ton), görs av lastbilar tyngre än 55 ton och de kan färdas upp till 1000 km på en tank. Som jämförelse har Hyundai Xcient, den första serieproducerade vätgaslastbilen tillgänglig i Europa, en räckvidd på 400 km och en maxvikt på 36 ton. Nikola Motor Co. lovar en räckvidd på över 1000 km för deras Nikola Two, som förväntas finnas tillgänglig på den amerikanska marknaden tidigast 2024, och maxvikten kommer även där vara begränsad till 36 ton. I dagsläget uppskattas vätgaslastbilar kosta 25% mer än traditionella lastbilar men kan redan 2027 vara kostnadseffektiva sett ur ett totalkostnadsperspektiv.

I Sverige finns enbart fyra fungerande tankstationer för vätgas varav en ligger i Sandviken. I Hofors planerar Ovako att bygga en världens största elektrolysörer för sin egen stålproduktion[2]. Gävle hamn undersöker också möjligheten att bygga en elektrolysör inom sitt område med en anslutande tankstation. I Borlänge har Maserfrakt fått pengar från klimatklivet för att bygga en tankstation för vätgas. Lokaliseringen till dessa platser är strategiskt viktig eftersom E16 är en populär rutt för tung godstrafik i Dalarna och Gävleborg till och från hamnen i Gävle. Befintliga och planerade tankstationer skulle kunna förse vätgas till ca 50 stycken vätgaslastbilar.

Den vanligaste källan till vätgas idag är naturgas som ger upphov till stora utsläpp av växthusgaser. För att vätgaslastbilar ska kunna minska utsläppen är det kritiskt att vätgasen produceras med förnyelsebara energikällor. Den dominerande tekniken för förnyelsebar vätgas förväntas vara elektrolysörer. Genom elektrolys delas vattenmolekyler med hjälp av elektricitet, för att producera vätgas, syrgas och värme. Det finns fyra huvudsakliga tekniker för elektrolysörer, alkalisk elektrolysör, protonutbytesmembran (PEM), anjonutbytesmembran (AEM) och högtemperaturelektrolys (SOEC). Detaljer om teknikerna finns i S1.

[2] Anläggningen som genomförande planeras bli 17 MW skulle bli en av de största om den färdigställdes idag. Andra bolag (utanför Sverige) har annonserat anläggningar om 100 MW, vilket är betydligt större än vad som finns idag.

S1. De fyra huvudsakliga metoderna för elektrolys med tillhörande nyckeltal (*state-of-the-art*)

Elektrolysör	**Alkalisk**	**PEM**	**AEM**	**SOEC**
Temperatur	50–80°C	70–90°C	40–60°C	700–850°C
Elektrolyt	flytande	fast (polymer)	fast (polymer)	fast (keramisk)
Elektrisk verkningsgrad (Low heating value)	50–68%	50–68%	52–67%	75–85%
Effektivitet vätgas	50–78 kWh/kg H_2	50–83 kWh/kg H_2	57–69 kWh/kg H_2	40–50 kWh/kg H_2
Livslängd bränsleceller	60,000 h	50,000 – 80,000 h	> 5,000 h	< 20,000 h
Mogenhet	Kommersiell	Tidig kommersialisering	Forskningsstadie	Forskningsstadie
Fördelar	• Mogen teknologi • Bevisat lång livslängd • Låga investeringskostnader • Icke-ädla material	• Hög strömöverföringskapacitet • Enkel design • Kompakt design • Dynamisk drift • Kort responstid • Reversibel process	• Icke-ädla material • Icke-frätande elektrolyt • Kompakt design • Låga investeringskostnader • Inget vätskeläckage	• Hög verkningsgrad • Icke-ädla material • Låga investeringskostnader • Reversibel process • Co-elektrolys möjlig
Nackdelar	• Utrymmeskrävande • Låg strömöverförings-kapacitet • Frätande elektrolyt • Icke-dynamisk drift • Blandning av gaser	• Dyrt membran • Ädelmetaller • Frätande miljö för cellerna	• Låg strömöverförings-kapacitet • Snabb degradering av membranet • Kraftiga spänningsfall	• Utrymmeskrävande • Ostabila elektroder • Läckage • Ömtåligt material
Lämplig i samband med en intermittent energikälla	Låg	Hög	Hög	Låg

Produktionskostnaden för vätgas via elektrolys är idag högre än för fossil vätgas. Det är dock svårt att säga exakt, då kostnaden varierar kraftigt beroende på källa. Kostnaden för elektrolysörer väntas sjunka kraftigt i samband med att den globala produktionskapaciteten förväntas stiga från 0.07 GW i 2019 till 25 GW 2030. Alkalisk elektrolys är idag den mest kostnadseffektiva metoden men PEM blir sannolikt den vanligaste metoden i samband med att tekniken mognar. Så mycket som 80% av produktionskostnaden kan vara el. På grund av Sveriges låga elpriser har Sverige potential att få ett av världens lägsta vätgaspriser. Redan 2025 kan det vara möjligt att producera vätgas så billigt som 3 EUR/kg, vilket kraftigt skulle öka vätgaslastbilars attraktivitet.

Ett sätt att minska kostnaderna är att ta till vara på och sälja biprodukterna syrgas och värme. Lokaliseringen av en anläggning kan därför bli viktig för att öka lönsamheten. Stålindustrin förbrukar mycket syrgas men ett annat intressant alternativ kan vara landbaserade fiskodlingar som behöver stora mängder av både syrgas och värme.

För att möta Sveriges energibehov förväntas vindkraft att behöva öka från dagens 20 TWh till 80 TWh i 2040. Vätgas kan genom elektrolysörer, och framförallt PEM, skapa förutsättningar för utbyggnaden av förnyelsebar energi genom att hantera intermittenta svängningar i eltillgången och höja kapacitetsfaktorn. Det är även möjligt för PEM att medverka på Svenska Kraftnäts balansmarknader för att bidra till att stabilisera elsystemets frekvens. Flaskhalsar i elnätet kan kosta Sverige så mycket som 8 miljarder EUR om året i samhällsekonomiska förluster till följd av effektbrist och även Gävle är påverkat. En regional utbyggnad av elektrolysörer kan därmed komplettera sol och vindkraft och spela en viktig roll i att attrahera företag till regionen. Tillgången till förnyelsebar energi var t.ex. avgörande när Microsoft valde att lägga sina datacenter i Sandviken och Gävle. För att fortsätta locka till sig utländska investeringar är det viktigt att garantera den regionala energitillgången.

Vätgaslastbilar är framförallt intressanta för att de har lägre miljöpåverkan än dagens lastbilar. Däremot är det svårt att exakt bedöma fordonens miljöpåverkan. Det saknas standardiserade metoder för livscykelanalys för fordon och tillgången till data för vätgasfordon är begränsad och i stor utsträckning baserad på simuleringar snarare än empiriska data. En bränslecell ger upphov till mellan 30 och 100 kg CO_2-ekv per kW_{max}. Platina i bränslecellerna har störst påverkan på utsläppen och en stor del av forskningen kring bränsleceller syftar till att minska andelen platina. Utsläppen för en vätgaslastbil är starkt beroende av elens ursprung. En well-to-wheel-analys visar att vätgas producerad med svensk elmix har fyra gånger lägre utsläpp än diesel, och vätgas producerad enbart med vindkraft har 16 gånger lägre klimatpåverkan (S2).

S2. *Well-to-wheel* jämförelse av växthusgasutsläpp för vätgas, diesel och HVO100

Bränsle	**g CO_2-ekv/ tkm**
Vätgas, vindkraft	3,4
HVO100	6,4
Vätgas, svensk elmix	13,2
Diesel	55,2

I rapporten har 190 lastbilar som dagligen transporterar gods till och från hamnen i Gävle undersökts.

Skulle alla lastbilar ersättas och köras på vätgas producerad med svensk elmix kan utsläppen minska med 70%, från 31 000 ton CO_2-ekv till 9 000 ton CO_2-ekv årligen. För det skulle det krävas ungefär 3 200 ton vätgas per år. I urvalet kördes ca 25% på biobränslen, antingen HVO100 eller RME. Biobränslen och framförallt HVO100 har så låga utsläpp så att ersätta dessa bränslen enbart har en marginell påverkan.

Lastbilar i Sverige med en totalvikt över 32 ton ger upphov till 94% av transportmängden för lastbilar över 3,5 ton, mätt i ton-km. Att ersätta dessa lastbilar med vätgaslastbilar kan markant minska utsläppen från vägtransporter. För att det ska vara möjligt, måste priset på lastbilarna sjunka samtidigt som lastkapaciteten förmodligen måste öka. Framförallt måste bränslecellslastbilar bli tillgängliga för den svenska marknaden och det finns en risk att det dröjer till 2025 innan de första serieproducerade bränslecellslastbilarna kommer till Sverige. Det är sannolikt att det kommer att finnas en utbyggd tankinfrastruktur för vätgas innan dess. Det gör det möjligt för lastbilar, som kör gods längs med E16 till och från hamnen, att tanka vätgas från dag ett.

Nyckelord: vätgas, bränsleceller, tunga lastbilar, hållbara transporter, elektrolysör, förnyelsebar energi

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1. Introduction

In 2018, 18% of global greenhouse gas (GHG) emissions arose from road transportation (IEA, 2019a). As the globalization trend continues, the transportation of goods, and resulting emissions, is expected to sharply increase in the years to come (International Transport Forum, 2015). At the same time the need to reduce GHG emissions is clear. The UN climate agreement has been signed by 195 countries, with the goal to maintain the global temperature increase below 2°C (United Nations, 2015). However, scientists and experts warn that current efforts are not enough (Ripple et al., 2019).

Reducing GHG emissions despite an expected increase in overall transportation requires, among other things, adopting new technologies and fuel alternatives. Commonly discussed options are biogas and biodiesel (Arfan, 2019; Norell, 2019), as well as electromobility (Kjellén, 2020). Battery electric vehicles (BEV) and plug-in electric vehicles (PHEV) are most commonly associated with electromobility and as the technology has matured, prices for BEVs and PHEVs have gone down, driving range has increased and charging times have been reduced (Kjellén, 2020). In recent years, BEV and PHEV sales in countries like Norway, Sweden, Germany and the US (specifically California) have drastically increased.

Despite positive developments in the electric vehicle (EV) market, these have not included trucks and the road transportation of goods. The sheer battery size required puts trucks in a similar situation as cars were a few years ago, with high cost, short driving range and long charging times (Pohl et al., 2017). An increasingly attractive alternative for freight transport is the fuel cell electric truck (FCET). Fuel cells generate electricity which, coupled with a small battery, drives an electric motor. Like the BEV, the FCET has zero tailpipe emissions. The fuel cell system occupies less space and weighs less than the battery electric counterpart. Although still expensive, FCETs can offer competitive driving ranges and charging times compared to traditional diesel trucks (Pohl et al., 2017). Nikola Motor Company, an American start-up, boasts that their upcoming FCET, the Nikola Two, will offer a range of over 1,000 km and a refueling time of less than 15 minutes (Nikola Motor Co., 2021).

Fuel cells, with a few exceptions, are fueled by hydrogen gas (Mekhilef, Saidur, & Safari, 2012; Wilberforce et al., 2017). Hydrogen, which is commonly available in mixed form with oxygen, like in water and organic materials, is the most abundant element in the universe (Blaszczak-Boxe, 2015). Hydrogen gas is commonly used in industrial processes, such as oil refining, and steel and fertilizer production. Pure hydrogen is, however, rare, and almost 98% of the hydrogen gas is produced either from natural gas or coal (IEA, 2019b). For FCET technology to be a viable alternative to curb global warming, the hydrogen gas must be produced from renewable sources (Acar, Beskese, & Temur, 2018; Dincer & Acar, 2014). The most promising options include biogas reformation, gasification and electrolysis, a process of producing hydrogen using only electricity and water (Dincer & Acar, 2014; Holladay et al., 2009; Nikolaidis & Poullikkas, 2017).

Hydrogen, if produced from renewable sources, can support countries' ambitions of moving to fossil-free economies, in particular in the transport sector. In Sweden, in 2018, 32% of total greenhouse gas emissions originated from transportation (Naturvårdsverket, 2020) and the Swedish government has committed to reductions of 70% for domestic transportation (excluding aviation) by 2030 compared to 2010 levels (Svenska Trafikutskottet, 2018). The County of Gävleborg has set a regional target of having 40% of fuel coming from renewable sources by 2025 (Länsstyrelsen, 2019). With road freight responsible for around 24% of road transportation emissions in Gävleborg (Länsstyrelsen, 2020), FCETs could support regional environmental targets.

A major drawback for FCETs is the lack of hydrogen supply, both production and distribution (FCHJU, 2019; IEA, 2019b). Sandviken in Gävleborg has one of only five hydrogen refueling stations (HRS) in Sweden (Vätgas Sverige, n.d.-a). The issue is a "chicken and egg" problem; without consumers of hydrogen, companies will not invest in infrastructure, and without supply, potential hydrogen consumers, like freight companies, will not buy FCETs. The International Energy Agency (IEA) therefore urges policy makers, industry and researchers to work together to reduce the thresholds for companies interested in building out renewable hydrogen infrastructure (IEA, 2019b).

Electrolysis, expected to be the predominant production method for green hydrogen, currently comes with a high cost (FCHJU, 2019; IRENA, 2019). As fueling costs consequently are even higher, this acts as a barrier for using hydrogen as a fuel. A way of mitigating the high cost, and reducing the fuel price, is by finding additional value streams from the production facility. Options include grid balancing services, improving wind and solar capacity factors, and supplying long-term electricity storage. Another solution is selling the oxygen gas and heat created as a by-product in the electrolysis process.

Gävleborg and the surrounding regions, specifically Dalarna, could be suitable for pioneering a hydrogen-based transport system. In 2016, the world's first electric road pilot was commissioned[3] along E16 between Sandviken and Gävle (Region Gävleborg, 2020a). E16 connects a number of large manufacturing companies with the biggest logistics center in the region, Gävle Hamn (Port of Gävle). The Port of Gävle is now conducting a pre-study to investigate the possibility of building an electrolyzer to supply freight companies with hydrogen (Vätgas Sverige, 2020b). Regional manufacturing companies are looking to develop more sustainable supply chains and FCETs are an opportunity to reduce transport emissions[4]. Companies like Ovako, Sandvik and SSAB, along E16, already use hydrogen in their steel production, while Linde Gas operates hydrogen electrolyzers in Sandviken and Borlänge[5]. Region Gävleborg intends for Gävleborg to become one of Sweden's foremost hydrogen regions (Region Gävleborg, 2020b). It is the only Swedish county to participate in the European "Hydrogen Valleys" collaboration. The platform, run by the European Commission, connects 30 regions in 13 countries committed to hydrogen development (European Commission, 2020a).

The purpose of this study is to support regional actors interested in taking steps towards a hydrogen-based economy by investigating the feasibility of hydrogen as a fuel for goods transportation in Gävleborg. To assist this purpose the following research questions are addressed:

- Which electricity-based production methods are viable options for supplying Gävleborg with low emission hydrogen fuel?
- How can regional electrolyzers create benefits and promote the buildout of hydrogen supply infrastructure?
- To what extent is it possible for regional road freight companies to use fuel cell electric vehicle trucks today and in the future?
- What is the potential environmental impact of replacing a share of conventional trucks with fuel cell electric vehicle trucks transporting goods to and from the Port of Gävle?

This report specifically looks at FCET and regional road freight, travelling to and from the Port of Gävle. Due to the heavy and predictable traffic, freight companies could guarantee to utilize specific volumes of hydrogen, encouraging investment in supply infrastructure. More than 94% of all road-transported goods, measured in tonne-km, is done by cargo trucks with a gross weight above 32 tonnes (Trafa, 2020). Heavy duty trucks (HDT) are also expected to be difficult to replace with battery electric trucks, therefore the report focuses on trucks above 32 tonnes. Hydrogen production in this report is limited to electrolyzers, as they are expected to account for the majority of the green hydrogen produced.

The primary audience for this report is small to medium-sized enterprises (SME), specifically the freight companies and companies looking to invest in, or supply components to, the hydrogen value chain in Gävleborg and companies looking to implement more sustainable supply chains. However, anyone interested in a hydrogen economy will benefit from reading this report.

[3] The project was decommissioned in 2020.
[4] Antti Vainio, Mellansvenska Handelskammaren, personal communication, May 22, 2020
[5] Nicklas Tarantino, Triple Steelix, personal communication, June 15, 2020

The report is structured as follows. Chapter 1 introduces the topic of transportation issues and FCETs, and the research questions of the report. How the study has been conducted is presented in Chapter 2. FCET characteristics, availability and fueling are presented in Chapter 3. Chapter 4 contains an overview of electrolysis production technologies. Chapter 5 looks at identified hydrogen projects in the region that could provide hydrogen fuel, and the connection between hydrogen, renewable energy and the electricity grid. Environmental implications of FCETs and the well-to-wheel GHG emissions of hydrogen are introduced in Chapter 6, and in Chapter 7, the potential to reduce GHG emissions in Gävleborg through FCETs is presented. In Chapter 8 the research questions are discussed and finally, Chapter 9 contains concluding remarks.

In this report hydrogen, hydrogen gas and H_2 are used interchangeably. Renewable hydrogen, fossil-free hydrogen and green hydrogen are used in the same fashion. In strict terms, the Swedish electricity is neither 100% renewable, fossil free nor green. However, Sweden has some of the world's lowest emissions from electricity production, and 99% of it is fossil free (Ekonomifakta, 2020b) and 66% is renewable (Ekonomifakta, 2020a). Sweden is also a net exporter of both renewable and fossil-free electricity.

2. Method

The methods used in this study are literature review and personal contact with regional and national actors. Literature references are mainly scientific, either from peer-reviewed scientific papers or from research reports. Google Scholar is the most prominently used search engine, while articles have been retrieved from publishers' databases like Elsevier and Springer. Although some search keywords related to EV have been used, the most common method to find relevant articles has been snowballing, a process of using references found in articles. Other literature references include newspaper articles and government reports, regulations, statistical databases, and company websites. Information from these sources has been found either through personal referral or Google search.

Mainly regional companies were contacted to understand their interest and commitment to the development of a green hydrogen infrastructure. Contact has been done either through direct connection over the phone or via email.

Part of the report contains calculations of GHG emissions caused by regional heavy-duty trucks and the opportunity for FCETs to reduce emissions. Data about emissions and transport work is collected from national databases and JRC (Joint Research Centre) is used for truck-specific data. Fuel consumption is based in personal communication with the Port of Gävle and Sveriges Åkeriföretag. Data has been compiled using Excel and the results, including sensitivity analysis of driving distances and emission factors, are available in Appendix B.

3. Fuel Cell Electric Trucks and Fueling

To reach a 70% reduction of road GHG emissions by 2030 (Svenska Trafikutskottet, 2018), public, private and goods transportation need to shift towards fossil-free alternatives. The car industry has seen a rapid shift towards battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV). Some countries have announced upcoming bans on internal combustion engines (ICE) within the next decade (Autoblog, 2020). Improved range and charging infrastructure coupled with declining prices and government incentives have made BEVs and PHEVs competitive with diesel and petrol cars (Kjellén, 2020). In Sweden almost 30% of new car sales are now either BEV or PHEV, compared with only 0.01% for fuel cell electric vehicles (Trafikanalys, 2020).

Battery and plug-in hybrid electric trucks have not reached the same maturity as cars. Short range, heavy batteries and long charging times are drawbacks, caused by the size and mass of the batteries required to operate large vehicles (Pohl et al., 2017). Due to a high energy efficiency (~ 90%), electric trucks are still of interest for the transport sector, particularly for local distribution and construction vehicles[6,7]. For longer distances and heavier goods, fuel cells and FCETs are expected to play an important role, offering competitive ranges and comparative fueling times to diesel trucks. In figure 1, the different application areas for battery and fuel cell electric trucks are outlined.

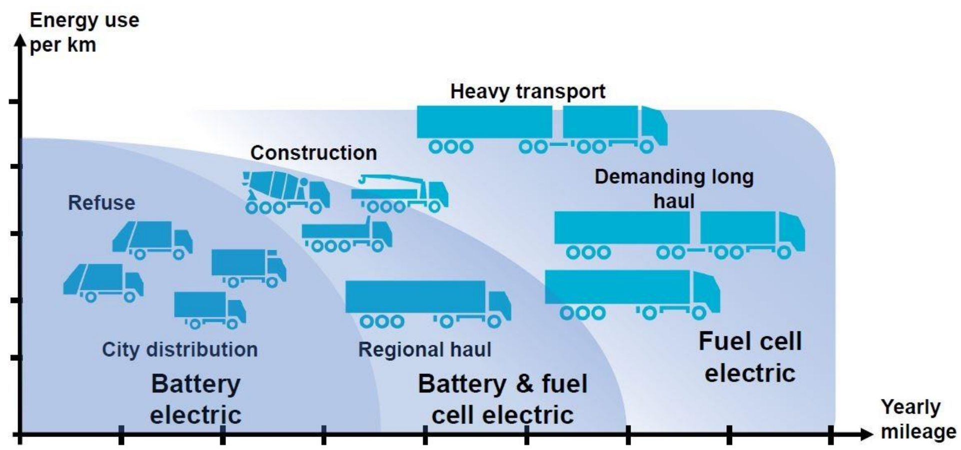

Figure 1. Comparison between battery electric trucks and FCETs and their expected application areas. Source: personal communication 11/26/2020: Johan Lindberg, Volvo Group

3.1 Fuel Cell Electric Truck

FCETs use an electric motor, similar to other electric vehicles. Hydrogen is fed to the fuel cells which in turn generate electricity to operate the electric motor. The system is complemented with a small electric battery, connected in parallel. The battery is used to stabilize power output and is charged either with the fuel cells or by taking advantage of regenerative braking, a concept of converting kinetic energy to electricity while decelerating (braking). An overview of the vehicle process is shown in figure 2. The only emissions from a fuel cell electric vehicle are water vapor (Vätgas Sverige, n.d.-b)

Tank-to-wheel (TTW) fuel cell efficiency is around 55% (Bethoux, 2020; Wilberforce et al., 2016). It can be compared to 30% for diesel trucks and 80% for battery electric trucks (Fiori & Marzano, 2018). For details on fuel cells for vehicle use, see Appendix A.

3.1.1 Payload and Weight

Fuel cell technology replaces the ICE drive train. Without a large combustion engine, FCETs have the potential to be lighter than their diesel counterparts, allowing a larger payload (European

[6] Personal communication 12/18/2020: Per Bondemark, Maserfrakt
[7] Personal communication 11/26/2020: Johan Lindberg, Volvo Group

Commission, 2020b). The world's first FCET model, the Hyundai Xcient, has a curb weight of almost ten tonnes (Hyundai, 2020), making it somewhat heavier than today's ICE trucks.

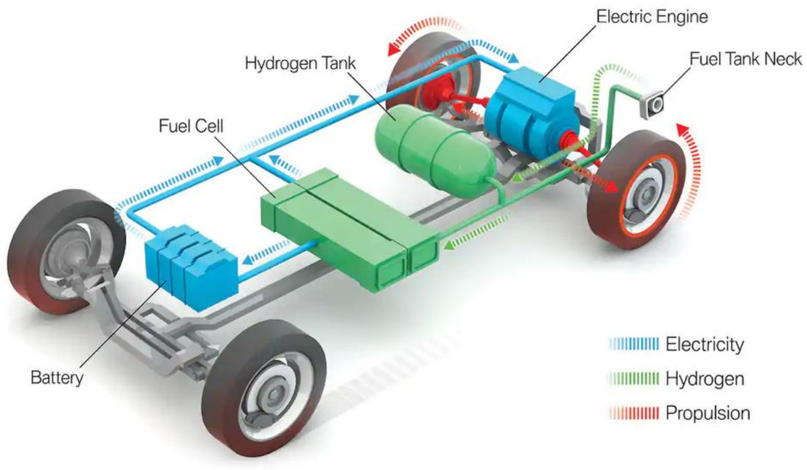

Figure 2. Principal schematic of a fuel cell electric vehicle. Regenerative braking, charging the battery from decelerating the vehicle, is omitted from the image. Source: BMW (n.d.).

In Sweden, the maximum allowed gross combination weight (GCW) for trucks is 64 tonnes, with some roads approved for 74 tonnes. Most of domestic road transport is done by trucks close to the limit. Based on weight, 70% of all goods are transported on trucks with a GCW above 55 tonnes (Trafa, 2020). In comparison, the first FCETs have or will have a gross combination weight rating of only 36 tonnes (Hyundai, 2020; Nikola Motor Co., 2021).

Power and torque are important metrics when determining a truck's ability to carry heavy loads. Drivers can expect FCETs to deliver on par or even outmatch common diesel trucks. The Hyundai Xcient has an electric motor with an equivalent 470 hp and 3,400 Nm torque (Hyundai, 2020). Nikola is set to offer 1000 hp on the first truck, Nikola Two, with 2,700 Nm torque (Nikola Motor Co., 2021).

3.1.2 Range and Fueling Times

A common concern with regards to electromobility is short driving ranges and long charging times (Pohl et al., 2017). Scania's recently released full battery electric truck, as an example, offers a driving range of 250 km, coupled with a 100-minute charging time (Scania, 2020). Compared to around 1,000 km and 15-minute fueling time for a diesel truck[8], the concern is understandable.

Hyundai, with a few delivered FCETs in Switzerland, promises 400 km range and fueling times between 8–20 minutes, with the goal to offer 1,000 km in their next generation of trucks (Hyundai, 2020), the same range as promised by Nikola Motor Co. for the rollout of their first truck Nikola Two (Nikola Motor Co., 2021).

3.2 Availability in Sweden

In Sweden and the Nordics, there are not many examples of FCETs today. Renova is operating a garbage disposal truck, running on fuel cells, delivered by Scania (Scania, 2018). The truck is custom built and is a refurbished diesel truck with the ICE replaced by fuel cells, built by the Swedish company PowerCell, with a battery and an electric motor. A second one is on the way (PowerCell, 2020). Scania has also delivered four distribution trucks, similarly built, to the Norwegian company Asko (Vätgas Sverige, 2020a). Custom-built FCETs, lacking economies of scale, have lead times of between 6 – 12 months and are available only at a significant cost premium[9,10].

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[8] Personal communication 12/15/2020: Roger Blom, Ernst Express
[9] Personal communication 12/15/2020: Boh Westerlund, Oazer
[10] Personal communication 12/18/2020: Per Bondemark, Maserfrakt

Currently there are no type built FCETs type approved for Swedish roads. Hyundai is the only supplier currently delivering type-built FCETs in Europe. The and delivered in 2020, the 50 first ever trucks to Switzerland (Hyundai, 2020), and are looking to expand to a handful more European countries in the coming years, Sweden not included (Eckert & Revill, 2021). An anticipated FCET is the Nikola Two from Nikola Motor, expected to be available on the US market in 2024 (Nikola Motor Co., 2021; Nikola Motor Co., 2020). Due to the long waiting list for Nikola Two, it is unclear when it actually will be available to Swedish companies[11]. Volvo and Daimler have announced a joint venture, Cellcentric, but do not expect to produce FCETs before 2025 (Cellcentric, 2021). Another company of interest is Hyzon, that expects to delivers their first FCETs in the Netherlands before the end of 2021 (Adler, 2021).

3.2.1 Pricing

Due to FCET being a new market there are large uncertainties regarding the price. Hyundai has signed a contract to deliver 1600 trucks in Switzerland. All trucks are leased, including hydrogen refueling stations (HRS) and hydrogen supply (Hyundai, 2020). Nikola has announced a similar model (Nikola Motor Co., 2021).

Deloitte & Ballard (2019) did a cost analysis for regional FCETs in the Los Angeles area. They found that FCETs are currently almost four times as expensive to purchase as an ICE counterpart (36 EUR vs. 10 EUR per 100 km), with total cost of ownership costs twice as high for FCETs (176 EUR vs. 92 EUR per 100 km). Assuming increasing costs for diesel and declining prices for production of FCET and hydrogen, FCET will break even with ICE in early 2028 (Deloitte & Ballard, 2019). Roland Berger & FCHJU (2020) expect FCETs to be 23% more expensive than diesel trucks in 2023 and estimate the FCETs can be cost competitive, from a total cost of ownership perspective, already in 2027.

3.3 Hydrogen Fueling

In Sweden there are currently four operational HRS, in Sandviken, Mariestad, Umeå and Stockholm, operating at either 350 or 700 bar (Vätgas Sverige, n.d.-a), and there are around 470 HRS globally (IEA, 2020). It can be compared to more than 2,500 public petrol stations in Sweden alone (Hittabensinstation.se, n.d.). In Europe there are only a few companies with experience of multiple HRS installations, Nel, Linde, and Air Liquide. In Sandviken today, hydrogen costs SEK 80/kg.

A critical question is how the hydrogen should be sourced. It can either be transported via trucks, like in Stockholm, or a pipeline, like in Sandviken or it can be produced directly on site, like in Mariestad and Umeå. The choice has a big impact on the total cost of installation.

An example is a HRS with on-site production capacity of 400 kg per day, able to supply around eight FCETs or 80 passenger vehicles. As a rough estimate, installing an electrolyzer can cost somewhere between EUR 1.6 – 1.9 million. A single fueling dispenser for trucks will cost at least EUR 1 million[12,13]. A compressor and generally some kind of storage are also required, which can easily add another EUR 0.5 – 1 million. In addition, the cost of design can amount to about 10% of total capital costs, increasing costs further. Due to the individuality of each project, estimates can vary a lot until the design phase is complete[14]. Consider instead building an HRS next to an existing electrolyzer, and the costs are reduced significantly. It is now possible to receive co-funding for HRS from the Swedish Environmental Protection Agency via the program “Klimatklivet”.

[11] Personal communication 12/15/2020: Roger Blom, Ernst Express
[12] Personal communication 03/12/2021: Anonymous
[13] Personal communication 05/27/2021: Boh Westerlund, Oazer
[14] Personal communication 05/27/2021: Boh Westerlund, Oazer

4. Hydrogen Production

Refined hydrogen is a common industrial gas used in oil refining, and the production of methanol, ammonia and steel (IEA, 2019b). The current hydrogen industry is roughly estimated at close to EUR 50 billion annually, assuming EUR 0.7/kg (Brown, 2019) and 70 million metric tons produced per year (IEA, 2019b). IEA (2019b) estimates that 98% of hydrogen today stems from either reformed natural gas (75%) or gasified coal (23%), causing 830 million tons of carbon dioxide (CO_2) emissions per year. It is roughly 16 times more than total Swedish emissions of 51.8 million tons CO_2 (Naturvårdsverket, 2020). S&P Global Platts (2019) estimates that if commercial fuel cell vehicles would reach 20% global market penetration it would almost double the current demand for hydrogen. It is clear that if hydrogen is to be a viable option for sustainable transportation it needs to be produced from fossil-free sources. The technology expected to produce the bulk of green hydrogen globally is electrolysis (FCHJU, 2019; IRENA, 2019), which will be covered in this report. Producing hydrogen from biomass via pyrolysis and gasification are other possible alternatives, but these are gaining considerably less interest so far.

4.1 Electrolysis Production Methods

Electrolysis is a process of applying electricity to water, splitting the water molecules to produce hydrogen and oxygen gas, and heat (Equation (1)). The process called electrolysis is similar to fuel cell technology; it is actually the reversed process, with a cathode, an anode, and an electrolyte. Unlike the fuel cell, the process uses electricity to produce hydrogen rather than consuming hydrogen to generate electricity.

$$H_2O + electricity \rightarrow H_2 + O_2 + \text{heat} \qquad (1)$$

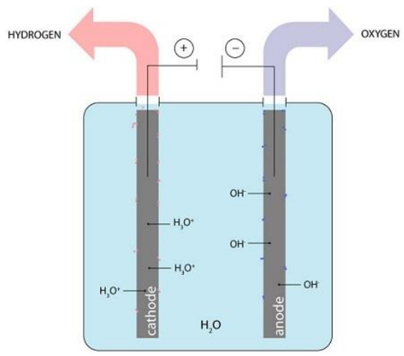

Figure 3. General process of alkaline electrolysis (Wassink, 2017)

There are four main electrolysis technologies: alkaline electrolysis, proton exchange membrane (PEM), anion exchange membrane (AEM), and solid oxide electrolysis cells (SOEC). Details of each technology are outlined in table 1.

4.1.1 Alkaline Electrolysis

Alkaline electrolysis is a mature technology, with low costs and proven long-term stability. A common application is chlorine production, where 5% global hydrogen is produced as a byproduct (IRENA, 2019). The electrolyte is a liquid solution where the cathode and anode are submerged, causing corrosion, and ultimately performance degradation of the system (El-Emam & Özcan, 2019; Sapountzi et al., 2017). The liquid electrolyte and a low current density, make alkaline systems significantly larger than PEM systems per MW (El-Emam & Özcan, 2019; IRENA, 2020). In the alkaline process, it is difficult to maintain a strict separation between the hydrogen and oxygen gases, reducing the purity of the hydrogen (Sapountzi et al., 2017). Alkaline typically operates at a temperature of 70°C with an energy efficiency of around 60%. It requires stable operating conditions making it unsuitable for use with intermittent energy sources such as wind and solar power (Byman, 2015).

Table 1. The four main electrolysis methods, state-of-the-art key performance indicators (IRENA, 2020)

Electrolysis	Alkaline	PEM	AEM	SOEC
Temperature	50–80°C	70–90°C	40–60°C	700–850°C
Electrolyte	liquid	solid (polymeric)	solid (polymeric)	solid (ceramic)
Voltage Efficiency (Low heating value)	50–68%	50–68%	52–67%	75–85%
Hydrogen efficiency	50–78 kWh/kg H_2	50–83 kWh/kg H_2	57–69 kWh/kg H_2	40–50 kWh/kg H_2
Stack lifetime	60,000 h	50,000 – 80,000 h	> 5,000 h	< 20,000 h
Maturity	Commercial	Early commercial	Research	Research
Advantages	• Mature technology • Long-term stability • Low capital costs • Non-noble materials	• High current density • Simple design • Compact design • Dynamic operation • Fast response • Reversible process	• Non-noble materials • Non-corrosive electrolyte • Compact design • Low capital cost • No leakage	• High energy efficiency • Non-noble materials • Low capital cost • Reversible process • Co-electrolysis possible
Disadvantages	• Bulky design • Low current density • Corrosive electrolyte • Non-dynamic operation • Gas permeation	• High membrane cost • Noble materials • Acidic environment	• Low current density • Membrane degradation • Large voltage drop	• Bulky design • Unstable electrodes • Sealing problems • Brittle ceramics
Intermittent power compatibility	Low	High	High	Low

4.1.2 Proton Exchange Membrane (PEM)

The PEM uses a solid polymeric membrane. H_2O is supplied at the anode where it splits into O_2 and hydrogen ions (H^+). The PEM operates at high pressure, and the membrane only lets through H^+, creating high purity hydrogen at the cathode. A solid membrane enables high power and gas densities, reducing the overall size per MW of the PEM (Carmo & Fritz, 2013; Sapountzi et al., 2017). However, the membrane is acidic. To maintain durability, noble materials are required, increasing the cost of the PEM stacks (El-Emam & Özcan, 2019; IRENA, 2020; Sapountzi et al., 2017). In past years, PEM durability has been low and lifetime only half compared to alkaline (Carmo & Fritz, 2013; Dincer & Acar, 2014). State-of-the-art PEM now has a competitive lifetime of between 50,000 – 80,000 hours (IRENA, 2020).

PEM has two significant advantages. Hydrogen yield and material deterioration are not dependent on stable operating conditions. The system can quickly and efficiently increase or decrease output without a problem. The PEM is also a reversible process, meaning that if supplied with hydrogen, it can generate electricity. That is an advantage in grids with intermittent power sources like wind and solar power (Byman, 2017; Carmo & Fritz, 2013). Such renewable sources have seen a rapid expansion in recent years and are expected to continue to grow in the foreseeable future. As a consequence PEM is becoming increasingly attractive (Parra et al., 2019).

4.1.3 Anion Exchange Membrane (AEM)

The AEM is currently only at the research stage but is receiving attention. With a solid membrane, and a small amount of liquid solution, it combines positive features of both alkaline and PEM. Compared to alkaline electrolysis, the solution is less corrosive, more compact, more stable, smaller in size, and easier to handle. Compared to PEM, it uses a less expensive membrane and needs no noble metals. A drawback is low conductivity, limiting the power output (Sapountzi et al., 2017; Vincent & Bessarabov, 2018). The current lifetime of the stacks is only a few thousand hours, compared to over 50,000 hours for alkaline and PEM. As the technology matures it is expected to reach the same lifetime as the other electrolysis technologies (IRENA, 2020). AEM can potentially, like PEM, provide electricity grid stability services (Ibid, 2020).

4.1.4 Solid Oxide Electrolysis Cells (SOEC)

SOEC operate at temperatures close to 1000°C, requiring electricity and significant amounts of heat (Byman, 2015; Dincer & Acar, 2014; Sapountzi et al., 2017). SOEC can, with an appropriate heat source, reduce electricity requirements by up to 25% compared to other hydrogen production methods (Bhandari, Trudewind, & Zapp, 2014). While electric efficiency can reach 100% (Carmo & Fritz, 2013; Sapountzi et al., 2017), overall system efficiency is low (40–60%) (Sapountzi et al., 2017). If SOEC facilities can access high-grade waste heat, it would improve the overall business case (Byman, 2015). Although offering a potential for mass production of hydrogen, drawbacks such as system stability and durability of the ceramic material in the electrolyte first need to be overcome (Carmo & Fritz, 2013; Sapountzi et al., 2017). Additionally, SOEC is unlikely to be suitable for power-to-grid applications based on renewables, since the load variability is low and SOEC should preferably operate with a constant power input (Bhandari et al., 2014; Byman, 2015). The process is reversible, however, making it possible to provide electricity to the grid (El-Emam & Özcan, 2019).

An attractive feature of SOEC, due to the high operating temperature, is the possibility to also produce synthetic gas (syngas) in the same process, reducing CO_2 and H_2O to CO and H_2, referred to as co-electrolysis (Carmo & Fritz, 2013; Sapountzi et al., 2017). Syngas is a popular gas in industrial processes and is used in the production of ammonia and fertilizer (Liu, Song, & Subramani, 2010)

4.2 Electrolysis Cost Trends

The literature regarding production cost for renewable hydrogen varies widely. PEM electrolyzers coupled with wind power alone, differ between 4,5–7.9 EUR/kg H_2. If other production methods and energy sources are included, the spread increases to 1–19.5 EUR/kg H_2 (Ball, Basile, & Veziroglu, 2016; El-Emam & Özcan, 2019).

One reason for the discrepancy is that electricity is a major cost driver for electrolysis. For a grid-connected facility it amounts to 80% of total costs. If electricity is purchased at EUR 84/MWh, the price of hydrogen would be around EUR 5.5/kg, according to the ICCT (2020). It can be compared to the Swedish average spot market electricity price of EUR 32/MWh[15] (Nord Pool, 2021). It suggests Swedish hydrogen producers can reach significantly lower production costs, due to low Swedish electricity prices. In fact the ICCT (2020) suggests that hydrogen can be produced at less than EUR 3/kg already in 2025.

In a recent report IRENA (2020) compares existing global electrolysis capacity of 0.07 GW in 2019 with the expectation of 6 GW and 25 GW capacity in 2025 and 2030, respectively. A rapid expansion of capacity will reduce installation costs over time. IRENA (2020) expects electrolyzer costs to go below EUR 200/kW in 2050. With alkaline costs ranging between EUR 840 and EUR 420 and PEM costs between EUR 1180 and EUR 590 today, it is a significant drop in price. Assuming a linear change in price, alkaline will cost between EUR 730 and EUR 380 and PEM between EUR 1000 and EUR 520 in 2025, see figure 4. Saba et al. (2018), in their literature review of the last 30 years, have found similar cost estimates. The reason PEM prices drop faster than alkaline is because it has not yet reached full market maturity.

[15] Considers data from the SE2 region, between January 2015 and October 2020, SE3 has a similar price

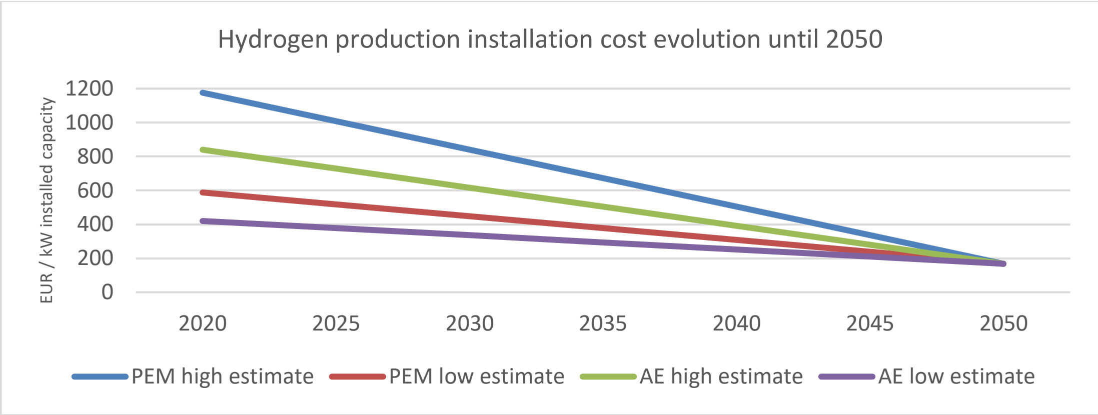

Figure 4. Alkaline and PEM electrolyzer costs today and projections for the future (IRENA, 2020)

5. Hydrogen Supply in Gävleborg & Dalarna

Hydrogen is a common industrial gas in Sweden. Oil refineries use the bulk (more than 70%), but regional companies like SSAB, Ovako and Sandvik all rely on hydrogen in their production processes (Fossilfritt Sverige, 2021). All hydrogen in Sweden is produced and consumed at the same location and it is a requirement to achieve competitive production costs for green hydrogen (Fossilfritt Sverige, 2021). Gävleborg and Dalarna, with their heavy steel industry, have been identified as a suitable hydrogen cluster (Fossilfritt Sverige, 2021). As the region develops more and more hydrogen infrastructure, it will create opportunities for many kinds of companies to create new hydrogen-related products, services and businesses. Already today hydrogen is used to produce biodiesel (HVO100). Colabitoil, for example, is a regional company that will require hydrogen as they expand the business to produce HVO100 locally (Colabitoil, 2020). Another Gävle-based example is Nitiu, looking to develop new storage solutions for the hydrogen gas (Nitiu, n.d.).

5.1 Regional Hydrogen Projects

For the trucking industry to access hydrogen there is a need for both production and fueling stations. At one location in the region, this is already possible, but more companies have expressed an explicit interest to access and source renewable hydrogen within the next few years.

5.1.1 Linde Gas

Linde Gas is the only large-scale producer of hydrogen from electrolysis in Sweden today. In total Linde Gas operates five facilities in Sweden. The two largest by far are located in Sandviken and Borlänge. The locations are based on the local industry demand, Sandvik in Sandviken and SSAB in Borlänge. Linde Gas also operates a fueling station suitable for both cars and FCETs. The available hydrogen capacity is not enough to maintain a large fleet of FCETs but is enough for any cargo company interested in piloting a small number of FCETs. While all Swedish facilities in operation today are alkaline, PEM is expected to be the dominant technology as the green hydrogen economy develops[16].

5.1.2 Ovako

Ovako is a large steel producer with a clear environmental agenda operating a facility in Hofors. While already consuming some hydrogen, Ovako is also looking to use hydrogen as a heating agent to replace liquefied petroleum gas. An estimated 7,000 m^3 of hydrogen per hour would be required to meet the demand in Hofors alone. Ovako is intent on initially building a 17 MW electrolyzer in Hofors, equivalent to 3,500 Nm^3 H_2 per hour. Without funding from initiatives like The Industry Leap ("Industriklivet"), the investment will not be possible. Ovako is hopeful that the rules for The Industry Leap will change to include hydrogen in 2021 to be able to produce onsite hydrogen already in 2022. While not including it in the business plan, Ovako invites third-party actors to install an HRS in connection to the expected electrolyzer in Hofors[17].

5.1.3 Port of Gävle

In Gävle, the harbor is a significant logistics center for regional companies[18]. Approximately 300 cargo trucks and over 15,000 tonnes of goods (including railway) pass through the harbor each day[19]. Hydrogen is likely to play an important role in the decarbonization of ships, making harbors a high potential hydrogen hub, enabling both road cargo and sea transport to use a carbon-free fuel (Balcombe et al., 2019). The Port of Gävle recently concluded a pre-study, with the intention of building a 2-3 MW electrolyzer operational in 2023[20,21]. A 3MW electrolyser and associated HRS will have the capacity to service almost 30 FCETs.

5.1.4 Maserfrakt

Maserfrakt, one of Sweden's largest distribution companies with over 1,600 vehicles and logistics trucks, has announced that they have secured SEK 7.7 million from the Swedish Environmental

[16] Personal communication 12/14/2020: Ola Ritzén, Linde Gas
[17] Personal communication 11/24/2020: Anders Lugnet, Ovako
[18] Personal communication 12/15/2020: Roger Blom, Ernst Express
[19] Personal communication 10/02/2020: Niklas Hermansson, Port of Gävle
[20] The Port of Gävle will not build and operate the electrolyser and are in discussions with third parties
[21] Personal communication 12/16/2020: Linda Astner, Port of Gävle

Protection Agency ("Naturvårdsverket") to build an HRS in Borlänge. Maserfrakt currently uses biodiesel (HVO100) for a lot of their trucks but HVO will be needed in large quantities to blend with diesel to meet reduction quotas in the future, potentially limiting the availability of HVO100. Hydrogen is another low-carbon fuel that can be used to complement biodiesel (Brodin, 2020, July 21st). Maserfrakt is not the only trucking company to believe biodiesel alone will not be enough to decarbonize the transport sector and that hydrogen is likely to play an important role for HDTs[22].

5.2 Hydrogen and Renewable Electricity Generation

Wind and solar power have become the most cost-efficient production methods for fossil-free electricity (FCHJU, 2019). In Sweden, electricity produced from wind has grown from 0.5 TWh in 2000 to 20 TWh in 2019, or from 0.3% to 12% of total electricity production (Energimyndigheten, 2020a). Industries are extensively becoming electrified, and until 2027, Swedish electricity needs are expected to increase by 20% (Svenskt Näringsliv, 2019). Besides the increased energy requirements, old non-renewable power generation, like nuclear, is replaced as it reaches end of life, requiring an even larger deployment of renewables. The Swedish Energy Agency (Energimyndigheten) (2019) estimates 60 – 90 TWh yearly wind production is required if Sweden is to have a fossil-free energy sector by 2040.

Electricity is the largest single cost component of producing hydrogen in electrolyzers (ICCT, 2020; IEA, 2019b). A determining factor of electricity prices is the power balance of supply and demand. An increasing portion of intermittent renewable energy supply (RES) accentuates price fluctuations and in 2020 Sweden for the first time experienced negative electricity prices at a point in time with low demand and very high wind power generation (Svenska Kraftnät, 2020c). Electrolyzers, in particular PEM, are suitable for varying load and can act as a supplement to RES to improve capacity factors and enable a faster buildout of wind and solar parks (FCHJU, 2019; IEA, 2019b; IRENA, 2020; Maggio, Nicita, & Squadrito, 2019).

In Sweden and other energy markets, balancing services is nothing new. Svenska Kraftnät, owner of the Swedish transmission grid, is responsible for maintaining a stable grid frequency. Today hydro power is the dominant power source, complemented by oil and gas, but Svenska Kraftnät (2019a) expects new, less traditional actors to enter the balancing markets. A system highly dependent on RES like wind and solar, will increase the need for storage and balancing services (Byman & Nordling, 2016; Svenska Kraftnät, 2019b). Actors participating in these markets can expect higher revenues in the future (Nohrstedt, 2020).

Typically, a high value balancing market has stringent requirements on for example response times and power flexibility (Svenska Kraftnät, 2020b). The PEM electrolyzer is a prime candidate for such services and, unlike alkaline and SOEC, it operates at high efficiency even during fast power fluctuations (Byman, 2015; IRENA, 2020; Sapountzi et al., 2017). Allidières et al. (2019) have shown, in tests, that PEM electrolyzers have enough flexibility (ability to operate under varying power conditions) and reactivity (response time) to participate in balancing markets with even the most stringent requirements. Another technology suitable for the balancing markets is the lithium-ion battery.

5.3 Gävleborg Power Supply

Hydrogen from electrolysis can provide support to local electricity grid issues. A lack of power capacity, primarily due to bottlenecks in the transmission grid, has become a pressing concern on a local and regional level in Sweden. A lack of power supply threatens regional growth, and the total Swedish socio-economic cost could already amount to EUR 8 billion per year due to a lack of power availability (Pöyry, 2018). The most affected regions are Stockholm, Uppsala and Västerås, but Gävle is also affected and might become more constrained in the future (Region Stockholm, 2019). Gävle Energi confirms that the county's excess power capacity has reduced[23]. New investments of EUR 7.5 billion have been announced by Svenska Kraftnät, in order to supply more power from northern Sweden to Stockholm and the surrounding regions. However, Svenska Kraftnät expects at least 20 years until project completion (Svenska Kraftnät, 2020a).

[22] Personal communication 12/15/2020: Roger Blom, Ernst Express
[23] Personal communication 10/30/2019: Hans Ädel & Teddy Hjelm, Gävle Energi.

Dybdal Christensen et al. (2018) identify Swedish RES as a way to attract foreign companies to settle in Sweden. When Microsoft chose Sandviken and Gävle as site locations for their data centers, access to RES was a deciding factor (Microsoft, 2019). Access to electricity in the region is not likely to improve as more companies are looking to electrify production. The Hybrit steel collaboration project between LKAB, SSAB and Vattenfall is expected to increase its electricity needs by 55 TWh on a national level until 2045, for hydrogen production alone (Fossilfritt Sverige, 2021). This is equivalent to around 40% of Sweden's current electricity demand (Energimyndigheten, 2020b). A regional example is Ovako, looking to install two electrolyzers, with a power requirement above 30 MW, equal to the power consumption of a medium-sized Swedish city.

A buildout of RES will be important to maintain regional attractiveness for new companies and existing ones looking to expand. Svea Vind Offshore, a company based in Gävle, is looking to develop 5 TWh of new wind power generation along the coast of Gävleborg (Blom et al., 2020), enough to meet the 2030 Gävleborg target for wind power (Länsstyrelsen, 2019). As mentioned in section 0, PEM electrolyzers can support wind power buildout, improve RES capacity factors and stabilize the grid. For that reason Svea Vind Offshore is looking to complement their wind development with hydrogen facilities[24]. Currently there is a three-year waiting time for a large electricity grid connection in the area. To continue to attract foreign investment in the area, a buildout of the regional energy supply is essential, for example by using wind power and hydrogen storage [25].

[24] Personal communication 10/20/2020: Mattias Värn, Svea Vind Offshore
[25] Personal communication 09/29/2020: Sam Cole, Invest in Gävleborg.

6. Environmental Impact

6.1 Environmental Impact of Fuel Cell Trucks

Assessing environmental impact from the production of vehicles is difficult. There is a lack of standardization in vehicle life cycle assessments and those with intimate knowledge of the production processes, the manufacturing companies, are reluctant to share internal results (Gröna Bilister, 2019). Fuel cell electric vehicles in general, and FCETs in particular, are a commercial novelty. Access to environmental impact data is limited and is largely based on simulations, rather than real world data (Usai et al., 2021).

Tahir and Hussain (2020) compared global warming potential (GWP) and other impact categories and concluded that, under a high penetration of renewables scenario, the production and materials of an FCET corresponds to over 30% of total life cycle emissions. The Colorado Energy Office (2019) compared the environmental impact from the complete life cycle of hydrogen-fueled buses and trucks against diesel and other alternative fuels. Assuming that hydrogen is produced from RES, it is the only alternative fuel that outperforms diesel for all the studied emissions[26].

Life cycle GHG emissions of fuel cell systems for cars can vary between 30 and 110 kg CO_2e/kW_{peak} (Evangelisti et al., 2017; Miotti et al., 2017; Notter et al., 2015; Simons & Bauer, 2015; Usai et al., 2021)[27]. The catalyst, containing a high concentration of platinum and the storage tanks, produced mainly using carbon fiber, have the largest effect on GWP in the fuel cell system. Looking across a larger set of impact categories, the platinum in the catalyst has the biggest negative impact of all parts (Usai et al., 2021)[28]. Platinum is a common material in catalytic converters of ICEVs and 40% of global annual production is used by the automotive industry, but fuel cells electric vehicles require around three times more platinum than a diesel car (Pollet, Kocha, & Staffell, 2019). However, development to reduce platinum content in fuel cells is improving fast, and there are several research examples of fuel cell catalysts reducing the platinum content by 80-90% from today's levels (Sievers et al., 2021).

6.2 Well to wheel emissions of hydrogen

GHG emissions from heavy road transport are mainly caused by the combustion of fossil fuels, diesel in particular. To compare hydrogen to the alternatives some assumptions about the production of hydrogen are required. Based on the input from regional actors, PEM electrolyzers seem the most likely to be actualized in the near term. To calculate FCET emissions, specific energy, density and energy requirements are needed (table 2). Combined with emission figures for Swedish electricity (table 3) it is possible to make an environmental fuel comparison.

Table 2. Specific energy, density and energyrequirements to produce and fuel hydrogen

Hydrogen Assumptions	
MJ/kg (LHV)	120
kWh /Nm^3 (production)	4.67
Density (kg/Nm^3)	0.084
kWh/kg (production)	55.6

Table 3 GHG emissions assumptions for Swedish grid mix and offshore wind generation

Electricity emissions	
Swedish energy mix (kg CO_2e/kWh)	0.047
Offshore wind (kg CO_2e/kWh)	0.012

[26] The studied emissions are GHG, CO, NO_x, PM10, PM2.5 and VOC. The study compares hydrogen (renewable and non-renewable), diesel, natural gas and biogas (compressed and liquefied), and electricity.
[27] Studies only consider light duty vehicles and the fuel cell system specifically, while other large impact contributors like the glider are excluded.
[28] Usai et al. (2021) consider GWP, Fossil Depletion Potential, Freshwater Eco-Toxicity Potential, Human Toxicity Potential, Marine Eutrophication Potential, Metal Depletion Potential, Particulate Matter Formation Potential, and Terrestrial Acidification Potential.

Measured in g CO_2e/MJ, hydrogen produced using only wind power is the most environmentally benign option available for heavy duty trucks (HDT)[29], closely followed by HVO100. HVO100 has fewer emissions than hydrogen produced when assuming an average Swedish electricity mix (Soam & Börjesson, 2020). “Swedish hydrogen” in turn, is significantly lower than diesel and petrol. Well-to-tank emissions do not, however, consider the complete picture. Each drive train has its specific (average) fuel consumption, impacting the total well-to-wheel emission, see table 4. The comparative order is unchanged, but the relative advantage has improved for hydrogen, making a stronger case to switch to hydrogen for HDT.

Table 4. Comparison of GHG fuel emissions for hydrogen, HVO100, FAME and diesel

Fuel type	**g CO_2e/MJ**	**MJ/liter (kg)**	**liter (kg)/km[a]**	**g CO_2e/km**	**g CO_2e/ tkm[a]**
Hydrogen, Wind	5.8	120[c]	0.069[d]	48	3.4
HVO100	8.8	34.3	0.30	92	6.4
Hydrogen, Swe mix	22.7	120[c]	0.069[d]	189	13.2
FAME/RME	32.1	33	0.31	334	23.3
Diesel[b]	77.2	35.2	0.29	789	55.2

a) Assuming a weighted payload of 14 tonnes, in accordance with European Commission (2020)

b) Based on Swedish 2019 levels of HVO blend in (23.3%) (Energimyndigheten, 2020c)

c) For hydrogen the unit used is MJ/kg

d) For hydrogen the unit used is kg/km

[29] Heavy duty trucks have different definitions. In Sweden all trucks above 3.5 tonnes are classified as heavy trucks (“Tung Lastbil”). Another classification is the CE driver license, required for a GCW above 12 tonnes. Due to the considerable amount of transport work done by trucks above 32 tonnes, this definition is used for heavy duty trucks (HDT) in this report.

7. Reducing Road Transport Emissions in Gävleborg

In Gävleborg more than 40% of GHG emissions originate from road transportation (compared to the national average of 32%). Trucks with gross combination weight above 3.5 tonnes are responsible for almost a quarter of the road emissions (Länsstyrelsen, 2020), and most transport work is done by trucks above 32 tonnes. The Port of Gävle loads and unloads large amounts of goods every day, connecting industry in the region with the continent. Much of the goods are transported to and from Dalarna.

FCETs have been assumed to be able to replace diesel trucks one-to-one, however, current FCET technology only allows for 36 tonnes GCW, which would require more FCETs to transport the same amount of goods as most HDT transport is done with GCW above 55 tonnes.

7.1 Introducing Fuel Cell Electric Trucks in Gävleborg and Dalarna

Regional transport is dependent on heavy duty trucks (HDT). About 84% of all deliveries are made within 150 km from its origin and 74% of the goods are loaded and unloaded in the same county. HDT are responsible for 94% of the payload-distance, measured in tonne-km (tkm). Based on national average, Gävleborg- and Dalarna-based HDT drive approximately 200 million vehicle-km each year (Trafa, 2020).

To understand the potential market for hydrogen, the Port of Gävle conducted a survey with cargo companies frequenting the harbor. A total number of 15 companies were interviewed and the results are shown in table 5[30].

Table 5. Summary results of interview study done by the port of Gävle, including number of HDT, and average and annual fuel consumption

HDT deliveries to Port of Gävle	Average fuel consumption (liters/HDT/day)	Total fuel consumption (liters/year)
190	233	13,800,000

The dominant fuel for HDT is diesel. In the sample, approximately 75% is diesel while 25% is either HVO100 or RME (considerably higher than the national average)[31].

With emission figures from Energimyndigheten (2020b), consumption figures from JEC (2020), and collected data from the Port of Gävle survey, the emissions caused by the HDT are estimated at 30,700 tonnes CO_2e per year (see table 6). The total driving distance for the interviewed companies amounts to almost 25% of all kilometers driven by HDT in Gävleborg and Dalarna.

Table 6. Summary results of interview study done by the port of Gävle, including number of HDT, and average and annual fuel consumption

Fuel	Emissions (kg CO_2e/l)	Fuel Consumption (l/100 km)	Fuel Consumption (million l/year)	Emissions (tonne CO_2e/year)	Driving distance (million km/year)
Diesel (MK1)	2.73	29.0	10.2	27,800	35.0
HVO100	0.3	30.4	1.2	350	3.8
FAME/RME	1.06	31.5	2.5	2,640	7.9
Total	-	-	13.8	30,700	46.7

A transition to a hydrogen-based freight system is unlikely to happen overnight. This report therefore considers three scenarios, displacing current fuels with 25%, 50% and 100% hydrogen, respectively (table 7). Preferably, hydrogen would displace only diesel. However, a possible scenario is that

[30] Personal communication 10/02/2020: Niklas Hermansson, Port of Gävle

[31] Based on national figures from the Swedish Association of Road Transport Companies ("Sveriges Åkeriföretag") and interviews with selected companies with an above average share of HVO100 and RME.

companies that today are focusing on biofuels like HVO100 and RME are also likely to adopt a new technology like hydrogen. Therefore, in the short term, there is a risk, despite diesel being the most environmentally harmful fuel, that HVO100 and RME will be displaced first. Thus, we consider both alternatives, displacing diesel first and biofuels first. Replacing all 190 trucks in the study would require almost 8,900 kg hydrogen per day, assuming an average hydrogen consumption of 47 kg hydrogen per day per truck.

Table 7. Hydrogen required to replace 25%, 50% and 100% of fuel for companies delivering goods to Port of Gävle

Replacement scenario	Fuel replaced first	Diesel consumed (l/year)	Biofuels consumed (l/year)	Emissions (tonnes CO_2e/year)	Hydrogen requirements	Replacement scenario	Fuel replaced first
0% (Base case)	None	10,200,000	3,650,000	30,700	0	0	0
25%	Biofuels	10,200,000	11,200	30,000	811,000	2,200	1,100
	Diesel	6,710,000	3,650,000	23,700			
50%	Biofuels	6,820,000	0	22,900	1,620,000	4,400	2,200
	Diesel	3,260,000	3,650,000	16,600			
100%	All	0	0	8,840	3,240,000	8,900	4,400

7.2 Localization and capacity of fueling stations

In Sandviken, one of only five HRS in Sweden is already operational. Ovako in Hofors, Port of Gävle in Gävle and Maserfrakt in Borlänge have intentions to build electrolyzers[32], with the hope of being able to deliver hydrogen to FCET in 2022. Ovako intends to use the gas for internal consumption but are positive towards a third-party actor installing an HRS. Assuming 5% of Ovako's hydrogen production can be offset for FCET, and a daily hydrogen need of 47 kg per day per truck, the existing and planned stations are able to supply enough gas for 52 trucks, more than required to meet the fuel displacement scenario of 25% and 48 HDT, see table 8.

Table 8. Overview of companies with existing or potential HRS, including electrolyzer size, location and service capacity

Company	Location	Electrolyzer (MW)	Production (~ kg H2 / day)	Service capacity (# FCET)
Linde Gas	Sandviken	-	-	5
Port of Gävle	Gävle	3	1,400	29
Ovako	Hofors	17	7,600	8
Maserfrakt	Borlänge	1	500	10
Total	-	21	9,500	52

The locations of the HRS are also strategically important as they are all placed somewhere along a heavily trafficked route on highway E16, or in the harbor. The road stretch connects, either directly or through connecting roads, several large Swedish industries with Port of Gävle. The locations of the HRS are mapped in figure 5.

[32] Maserfrakt is also considering sourcing hydrogen for a fueling station from local industry surplus or tank delivery, rather than building an electrolyzer.

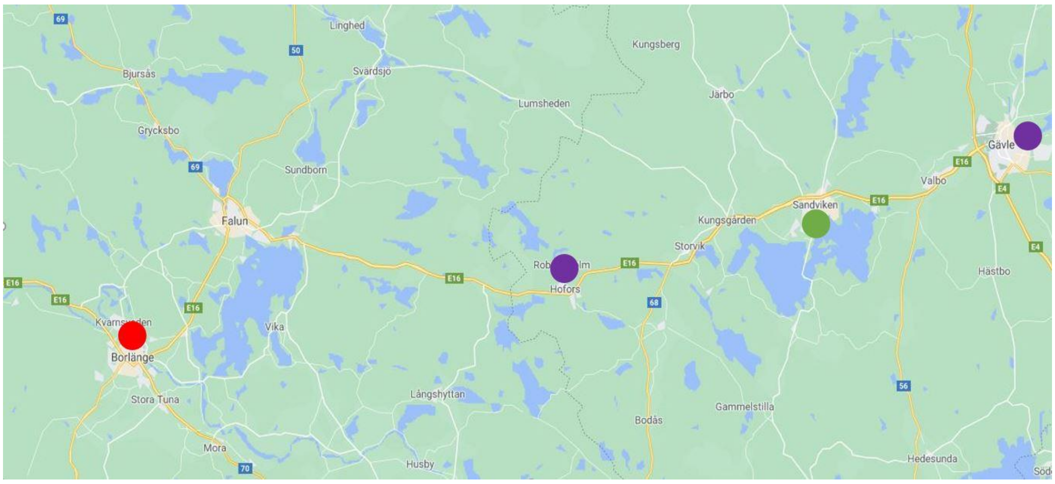

Figure 5 Localization of HRS in Gävleborg and Dalarna, green: existing HRS, purple: probable electrolyzer locations, red: planned HRS, specific location in Borlänge unclear

8. Discussion

The overall intention of this report is to assess the viability, and the opportunities and challenges for hydrogen as a fuel for heavy road transport in the region. To support this, four additional questions are posed and investigated. Each question is answered in order, starting with production methods. The second section in this chapter discusses leverage points for reducing the production cost of hydrogen. The following section brings up the viability for FCETs in the region in a short and medium-term perspective. Finally, the environmental aspects of FCETs and hydrogen as a fuel are discussed.

8.1 Electricity-Based Hydrogen Production

Hydrogen is the most common industrial gas but more than 95% of the hydrogen produced today is produced from either natural gas or coal. The global hydrogen industry today is responsible for GHG emissions 16 times larger than Sweden as a country. For hydrogen to be a viable alternative in the future, it needs to be produced from renewable sources. Hydrogen from electrolysis is considered to become the dominant technology pathway to produce green hydrogen.

Alkaline is the only technology fully commercial to date and all existing large-scale electrolyzers (globally) are alkaline. Alkaline has a long lifetime and low production costs relative to other electrolyzers. In the short term, alkaline seems to be the most attractive electrolyzer technology and is the preferred option for companies like Statkraft and Svea Vind Offshore, interested in operating hydrogen production facilities in Sweden[33,34].

PEM is reaching maturity with state-of-the-art longevity similar to alkaline. It is receiving attention largely because of the flexible load capacity, making it suitable to complement the intermittency of renewable energy sources like wind and solar. The membrane consists of noble metals like platinum, increasing production costs and the environmental impact. Ovako in Hofors are looking at PEM as the primary option for a potential hydrogen production investment[35].

AEM and SOEC are in the development stages with only a number of small-scale examples and limited life spans. In the long term they could prove to be attractive alternatives. AEM is a combination of alkaline and PEM, with almost no fluid, reducing corrosion, and with less noble metals than PEM, reducing the cost and environmental impact. SOEC operates at temperatures close to 1,000°C (compared to temperatures below 100°C for alkaline, PEM and AEM). The process is more dependent on heat, a lower grade energy source, than electricity. With access to high-temperature waste heat streams, total efficiency can reach above 100% (IRENA, 2020). Another advantage of SOEC is the possibility to co-produce hydrogen and syngas. Syngas is used in the production of, for example, ammonia and methanol, the largest consumers of hydrogen after the petroleum industry.

IRENA (2020) expect PEM electrolyzers to be about twice as expensive per kW as alkaline systems. However, the price drop on PEM has been significantly faster than academia, research institutes and others have anticipated, making the price difference between PEM and alkaline smaller than is generally accepted[36]. The biggest cost driver for production is electricity. It can amount to 80% of total hydrogen production costs (ICCT, 2020). Bloomberg (2020) estimates that Sweden and Scandinavia can supply green hydrogen at some of the lowest costs in the world due to the access to renewable energy sources and a low electricity price. Estimates suggest that production costs in Sweden can be almost as low as EUR 3 per kg. PEM is better suited to take advantage of fluctuating electricity prices than alkaline, providing an opportunity to lower operating costs.

8.2 Advantages of Regional Hydrogen Electrolyzers

Besides the obvious advantage of locally produced green hydrogen and job creation, other benefits can be seen from a buildout of hydrogen production capacity. They can be divided into two main categories, power supply and the use of by-products.

33 Personal communication 24/05/2021: Per Rosenqvist, Statkraft
34 Personal communication 03/12/2021: Karl Lindblad, Svea Wind Offshore
35 Personal communication 11/24/2020: Anders Lugnet, Ovako
36 Personal communication 03/12/2021: Karl Lindblad, Svea Wind Offshore

8.2.1 Power Supply

Due to the intermittent nature of wind and solar power, curtailment is not uncommon, when supply exceeds demand or when the grid is constrained. A clear example is the first case of negative electricity prices that occurred in Sweden in 2020. It is more common in Denmark, with a higher share of wind production, and it is likely to become more common in Sweden in the future.

PEM operates efficiently under varying load conditions. It can therefore increase and decrease production in correlation with the generation of wind and solar power. Not only does it allow the renewable sites to always operate at full capacity, the hydrogen facility also benefits from the lower power prices at times of excess electricity and reduced costs when there is a shortage of supply. As a consequence, it can reduce the need for grid infrastructure development, a process that is generally slow and costly. For the same reason, it can also enable a faster buildout of wind and solar parks. In doing this, it is also possible to participate in Svenska Kraftnät's balancing markets, earning money while supporting and maintaining a stable electricity grid.

Every year, billions of euros are not realized in Sweden due to a lack of power supply (Pöyry, 2018). In parts of Gävleborg, the waiting time for a regional grid connection is three years[37]. If hydrogen and new renewable energy sources are developed side by side, it can ensure that the regional industry continues to grow and is able to attract more foreign investments.

8.2.2 By-products

The main by-products of electrolysis are oxygen and heat, which can both be valuable to reduce the cost of hydrogen (Saxe & Alvfors, 2007). For each kilogram of hydrogen, eight kilograms of oxygen are produced. A 1 MW electrolyzer would produce around 3000 kg oxygen per day[38]. Oxygen is a commodity, industry is a large-scale consumer, whereas the health care sector needs oxygen on a small scale. Ovako, looking to install a 17 MW electrolyzer, has offset for all oxygen produced in the production process, improving the overall business case[39]. Another potential industry requiring vast amounts of oxygen is the fish farming industry[40]. In addition, combined heat and power plants can use oxygen to improve overall system efficiency[41]. Co-location of electrolyzers with industrial processes requiring oxygen can reduce the cost of hydrogen and oxygen for the involved companies.

The waste heat from electrolysis (excluding SOEC), is generally low temperature, and might be too low to directly connect to a district heating grid. An option is to install heat pumps to raise the temperature (Fang et al., 2013). Connecting to other heat users is another way to take advantage of the generated heat. Fish farming is again a good candidate, but another option is greenhouses.

8.3 Access to Fuel Cell Electric Trucks in Gävleborg

The possibility of using FCET in the region is dependent on two main factors, the availability and competitiveness of hydrogen-fueled trucks and access to hydrogen fuel.

In Sweden there few examples of retrofitted FCETs and custom-built FCETs come at a very high cost and are not likely to be purchased without grants or external funding. Hyundai is the only truck manufacturer producing type-built FCETs but does not deliver trucks to the Swedish market and only accepts large order volumes. Nikola Motors' flagship Nikola Two will likely not be available in Sweden before 2025. Volvo has announced a collaboration with Daimler, but also does not expect to produce any trucks before 2025. In reality, it will be at least a few years until FCETs reach the Swedish market. Due to the novelty, it is difficult to say much about FCET purchasing costs. Both Hyundai and Nikola have announced leasing models, including the cost and infrastructure for hydrogen fuel. As the market becomes more developed, it is more likely that trucks will be available for purchase without fuel and fueling stations.

Trucks with a gross combination weight above 36 tonnes are responsible for a majority of Swedish road deliveries and almost 90% of all transport work (in tkm) is done with a gross combination

[37] Personal communication 09/29/2020: Sam Cole, Invest in Gävleborg
[38] Assuming 55 kWh per kg H_2 and around 90% capacity rate
[39] Personal communication 11/24/2020: Anders Lugnet, Ovako
[40] Personal communication 03/22/2021: Emil Lindfors, Western Norway University of Applied Sciences
[41] Personal communication 03/24/2021: Johan Thelander, Karlstad Energi

weight above 55 tonnes. Even the heaviest trucks can reach up to 800 km on a single tank. As comparison, the Hyundai Xcient, launched last year in Switzerland, offers a range of 400 km with a maximum gross combination weight of 36 tonnes. The Nikola Two is expected to reach 1,000 km, but still only be able to carry a total weight of 36 tonnes. It is clear that the first-generation FCET will not be able to compete with the heaviest trucks and long haul on Swedish roads, but is more likely to find more local applications, carrying less payload over shorter distances, possibly competing with battery electric trucks.

Sandviken is one of only four locations in Sweden where it is possible to fill up hydrogen fuel today. The Port of Gävle is looking into the possibility of building a 2-3 MW electrolyzer. Ovako is intent on building one of the world's largest PEM electrolyzers in Hofors (17 MW) and Maserfrakt has been granted co-funding to build a HRS in Borlänge. The four combined locations should be able to supply at least 50 FCETs per day. This will be enough to accommodate early FCET adopters. Considering the timelines, it is highly probable that the three planned electrolyzer projects will be completed before FCETs reach the Swedish market. All four locations are based in the strategically important transport cluster, along E16 and the harbor, a road with a lot of shuttle traffic between the Port of Gävle and industries like Ovako, Sandvik and SSAB.

8.4 Environmental Impact of FCET

Like BEV, FCETs produce no tailpipe emissions. It is one of the main drivers for a transition towards a fossil-free society. Like BEV though, a side effect is the shift towards more environmental impact in other stages of the life cycle. In particular, the fuel cells contain platinum, a noble metal, potentially causing significant environmental impact in the supply phase. PEM electrolyzers, built in the same way, have the same problem. To be a long-term viable alternative, it is important to reduce the amount of noble metals in the system. Fortunately, the metals are major cost drivers in the systems, creating economic incentives to reduce the dependency on platinum and such.

The process of producing hydrogen through electrolysis requires electricity. The way the electricity is produced plays a major role in the overall well-to-wheel GHG efficiency. Producing hydrogen using the average EU electricity mix, heavily dependent on coal and natural gas, is not an option to reduce emissions. Sweden and the Nordic region are in a unique position with electricity almost completely fossil free, able to produce hydrogen with significantly lower emissions than diesel. Even so, hydrogen produced solely by wind emits four times less emissions than hydrogen based on Swedish average energy mix (including import). The comparison is available in table 9.

Table 9. Comparison of well-to-wheel GHG emissions between hydrogen, diesel and HVO100

Fuel type	g CO_2e/ tkm
Hydrogen, Wind	3.4
HVO100	6.4
Hydrogen, Swe mix	13.2
Diesel	55.2

This report investigates HDT transporting goods to and from the harbor in Gävle, a major logistics node in the region. There, 15 companies are responsible for an average of 190 HDT reaching the harbor every day with yearly GHG emissions of 30,700 tonnes, assuming Swedish energy mix. It is equivalent to almost 25% of all GHG emissions caused by trucks above 3.5 tonnes in the region. The 190 HDT consume approximately 13,800,000 liters of fuel in the form of diesel, HVO100 and FAME, each year. Replacing all HDTs with FCETs would require more than 3,000 tonnes of hydrogen annually and would reduce emissions by more than 70%. Replacing only 25%, or 48 HDTs, would reduce emissions by 7,000 tonnes (23%) per year. A risk however is that companies using biofuels like HVO100 and FAME are the early adopters and that an early introduction of FCETs would simply shift fuel consumption from one good alternative to another one. If that were the case, the first 48 HDTs would only reduce emissions by 800 tonnes (2.6%). Looking at GHG emissions HVO is a very advantageous fuel. It is considered crucial to Swedish targets of 70% emissions reduction until 2030, with a 66% blend in with diesel in 2030 (Energimyndigheten, 2019b). HVO can also be suitable for intercontinental long hauling, a segment where it might be difficult for battery electric trucks and FCETs to excel. Expanding the system boundaries to include a national perspective, even displacing biofuels in an initial stage is probably beneficial, as the biofuels will be made available elsewhere.

A limitation of the report is that it does not consider the reduced payload capacities of FCETs. Only being allowed a GCW of 36 tonnes would increase the number of trips required and thereby diminish the environmental benefits. The 36-tonne GCW limitation would effectively double the transport requirement.

9. Conclusion

To understand the feasibility of hydrogen as a fuel for goods transport to support regional actors interested in sustainable transportation, this report covers hydrogen production methods, potential access to hydrogen, availability and competitiveness of FCET, and environmental impact.

Alkaline is the most mature technology but the adaptability of PEM to support renewable integration and provide grid stability promotes an adoption of PEM in the long term, especially since grid stability and power access are important factors to enable growth and attract new companies to the region. The price for PEM is still higher than for alkaline but if PEM can create additional revenue streams, like price arbitrage[42], balancing services and by-products, it may soon prove to be a cost-efficient solution. Access to low emission, low cost electricity is a significant argument for new hydrogen production.

Projects considered by Ovako, Port of Gävle and Maserfrakt will provide hydrogen refueling access. If it is possible to produce hydrogen below EUR 3/kg, as suggested by the ICCT (2020), it can provide cheap fuel, reducing overall costs for freight companies.

If hydrogen is used to displace diesel, the most common fuel for HDT, the emission reduction potential is large. It is important that companies continue to use biofuels like HVO100 and RME, as it will be a long time until FCETs can reach a high penetration. There is a risk that environmental impact is shifted upstream in the value chain, in particular in the use of platinum in PEM fuel cells and electrolyzers. Research to reduce noble metal dependency is important for the long-term viability of hydrogen.

Costs for FCETs are still high and the trucks are also not accessible in Sweden, a major barrier for Swedish companies looking to transition to more sustainable alternatives. Range, but particularly payload capacity also needs to improve to be competitive for the region. While 400 km is enough for a round trip from Port of Gävle to Mora or Kopparberg in Dalarna, a significant number of trucks are carrying loads with gross combination weights above 55 tonnes. The gross combination weight limitation of 36 tonnes would, by a rough estimate, double the payload-distance in tkm (same weight, double the km). It would reduce the environmental benefits significantly and it is important to develop trucks able to carry heavier loads to support a transition to more sustainable transport.

Interesting future work includes the societal benefits of hydrogen, including the side benefits of PEM electrolyzers and its combination with renewable energy. The impact of hydrogen for HDT should also be combined with other aspects of road transport, such as the shift towards electric vehicles for personal cars, to see if the region can reach its climate targets.

[42] Price arbitrage takes advantage of differences in market prices. In the context of electrolyzers it means to increase hydrogen production when electricity prices are cheap and reduce production when they are high

10. References

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Appendix A

Fuel cell technology is similar to that of regular batteries. Two electrodes, anode and cathode, are connected through a metal wire, a transfer medium (an electrolyte or solid membrane) and a separator. At both electrodes, a chemical reaction occurs. The difference is that a battery is a closed system and only electricity is either applied or discharged. Fuel cells instead use externally added fuel to produce electricity. Hydrogen is most commonly used, but there are also some fuel cell technologies that can use carbohydrates, such as methane (CH_4), methanol (CH_3OH) and carbon monoxide (CO), as fuel. The fuel is supplied at the anode and reacts with the electrolyte to separate into protons (H^+) and electrons (e^-). The protons travel through the electrolyte while the electrons are forced through the metal wire to produce electricity. At the cathode protons and electrons react with oxygen and create water (Mekhilef et al., 2012; Saxe, 2008). The reactions are displayed in equation (2), (3) and (4) and a principal schematic can be seen in figure 6.

$$hydrogen + oxygen \rightarrow water + electrical\ power\ (+\ heat) \quad (2)$$
$$Anode: 2H_2(g) \rightarrow 4H^+ + 4e^- \quad (3)$$
$$Cathode: O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O\ (l) \quad (4)$$

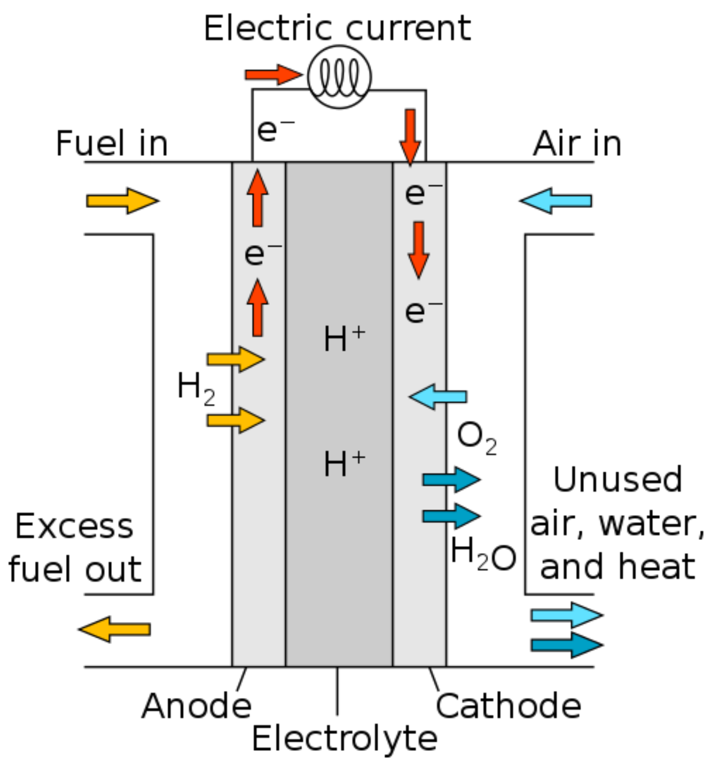

Figure 6. Schematic overview of the proton exchange membrane fuel cell

There are mainly six types of fuel cell technologies, each with specific operating conditions. However, only a couple are suitable for transportation, of which only the proton exchange membrane fuel cell (PEMFC) uses hydrogen as a fuel. The PEMFC also has a robust system design and operates at low temperatures with a comparatively high power density, fast response time, and little risk of corrosion and leakage, making the PEMFC the de facto standard for vehicle fuel cells. The major drawback of PEMFC is the use of the noble material platinum in the cathode, increasing the cost of production (Alaswad et al., 2016; Mekhilef et al., 2012; Saxe, 2008; Wilberforce et al., 2017). Readers interested in the other fuel cell technologies are encouraged to read Mekhilef et al. (2012).

Appendix B

Summary - Fuel 100%, Emissions 100%	Total H2 consumed (kg/year)	Total Emissions - Swe Mix (tons CO2e/year)	Total Emissions - Wind power (tons CO2e/year)	H2 - Prod (kg/hour)	H2 - Prod (Nm3/hour)
#0 - "Business as usual"	-	30,740	30,740	-	-
#1 - 25% replacement diesel first	810,980	23,689	22,044	93	1,102
#2 - 50% replacement diesel first	1,621,960	16,639	13,348	185	2,204
#3 - 100% replacement	3,243,919	8,840	2,257	370	4,408
#4 - 50% replacement biodiesel first	1,621,960	22,940	19,649	185	2,204
#5 - 25% replacement biodiesel first	810,980	29,968	28,322	93	1,102

Summary - Fuel 80%, Emissions 100%	Total H2 consumed (kg/year)	Total Emissions - Swe Mix (tons CO2e/year)	Total Emissions - Wind power (tons CO2e/year)	H2 - Prod (kg/hour)	H2 - Prod (Nm3/hour)
#0 - "Business as usual"	-	30,740	30,740	-	-
#1 - 25% replacement diesel first	648,784	23,247	21,931	74	882
#2 - 50% replacement diesel first	1,297,568	15,755	13,122	148	1,763
#3 - 100% replacement	2,595,135	7,072	1,806	296	3,527
#4 - 50% replacement biodiesel first	1,297,568	22,056	19,423	148	1,763
#5 - 25% replacement biodiesel first	648,784	29,526	28,210	74	882

Summary - Fuel 120%, Emissions 100%	Total H2 consumed (kg/year)	Total Emissions - Swe Mix (tons CO2e/year)	Total Emissions - Wind power (tons CO2e/year)	H2 - Prod (kg/hour)	H2 - Prod (Nm3/hour)
#0 - "Business as usual"	-	30,740	30,740	-	-
#1 - 25% replacement diesel first	973,176	24,131	22,157	111	1,323
#2 - 50% replacement diesel first	1,946,352	17,523	13,573	222	2,645
#3 - 100% replacement	3,892,703	10,608	2,708	444	5,290
#4 - 50% replacement biodiesel first	1,946,352	23,824	19,875	222	2,645
#5 - 25% replacement biodiesel first	973,176	30,410	28,435	111	1,323

Summary - Fuel 100%, Emissions 80%	Total H2 consumed (kg/year)	Total Emissions - Swe Mix (tons CO2e/year)	Total Emissions - Wind power (tons CO2e/year)	H2 - Prod (kg/hour)	H2 - Prod (Nm3/hour)
#0 - "Business as usual"	-	30,740	30,740	-	-
#1 - 25% replacement diesel first	810,980	23,247	21,931	93	1,102
#2 - 50% replacement diesel first	1,621,960	15,755	13,122	185	2,204
#3 - 100% replacement	3,243,919	7,072	1,806	370	4,408
#4 - 50% replacement biodiesel first	1,621,960	22,056	19,423	185	2,204
#5 - 25% replacement biodiesel first	810,980	29,526	28,210	93	1,102

Summary - Fuel 100%, Emissions 120%	Total H2 consumed (kg/year)	Total Emissions - Swe Mix (tons CO2e/year)	Total Emissions - Wind power (tons CO2e/year)	H2 - Prod (kg/hour)	H2 - Prod (Nm3/hour)
#0 - "Business as usual"	-	30,740	30,740	-	-
#1 - 25% replacement diesel first	810,980	24,131	22,157	93	1,102
#2 - 50% replacement diesel first	1,621,960	17,523	13,573	185	2,204
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