Prestudy H_2ESIN: Hydrogen, energy system and infrastructure in Northern Scandinavia and Finland

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Front page illustration: *Bridges over Torne river. Torne river defines a large part of the border between Sweden and Finland.*

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The project consortium consisted of additional 24 organisations representing a wide range of stakeholder groups: ABB AB, Business Sweden Business Support Office AB, Fortum Sverige AB, Fu-Gen Energi AB, Grupo Fertiberia, H2GS AB (H2 Green Steel), Investeringar i Norrbotten AB, Lhyfe Sweden AB, Linde Gas AB, Liquid Wind AB, LKAB, Node Pole, Nordion Energi AB, Region Norrbotten, Skellefteå Kraft AB, SSAB AB, St1 Sverige AB, Statkraft Hydrogen Sweden AB, Svenska kraftnät AB, SWECO Sverige AB, Uniper, Vattenfall AB, W3 Renewables AB (W3 Energy), and WPD Offshore Sweden AB.

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RISE Research Institutes of Sweden is an independent, state-owned research institute. As an innovation partner for every part of society, we help develop technologies, products, services and processes that contribute to a sustainable world and a competitive business community. We do this in collaboration with and on behalf of companies, academia and the public sector. For the context of this report, RISE offers support and expertise to businesses covering the hydrogen value chain from production of hydrogen, safety and regulations, materials and components to storage and implementation. In addition, RISE is the project coordinator for the Swedish Hydrogen Development Center, which is a knowledge center where both individual components and entire value chains for a range of different hydrogen applications can be tested and evaluated.

CH2ESS - Centre for Hydrogen Energy Systems Sweden is an extensive research and education investment at Luleå University of Technology with a focus on hydrogen use in industrial processes and energy systems, in close collaboration with Swedish industry. The research initiative takes a holistic approach to the production, transport, storage and use of hydrogen and includes process integration and the electric power system. CH2ESS is designed to support the ongoing implementation of hydrogen with subject excellence and multidisciplinary research, in cooperation with stakeholders worldwide. At Luleå University of Technology, the demand-driven research and education go hand in hand, which means that our research areas have a strong connection to our educations - with benefit for society. CH2ESS contributes to competence building and introduction of hydrogen in the society over the complete hydrogen value chain.

Disclaimer

As this is a prestudy report, the results and conclusions presented give a preliminary overview of the research area and point towards future opportunities and needs. This is important to keep in mind when reading the report. For example, the scenarios used for the preliminary techno-economic analysis are meant to cover a spectrum of outcomes. The individual scenarios are neither suggestions for the future nor meant to describe possible futures. Instead, the scenarios illustrate and point out important parameters in a future hydrogen energy system. These parameters are the basis for further research needs identified in the report.

Executive summary

This prestudy has been conducted by RISE Research Institutes of Sweden and Luleå University of Technology and has been carried out together with additional 24 stakeholders interested in a hydrogen energy system in northern Sweden. The study was financed by Sweden's innovation agency (Vinnova) and the participating organisations.

The purpose of this report is to analyze the conditions, opportunities, and obstacles for the development of a hydrogen infrastructure in northern Scandinavia and Finland. The objective is to present an updated picture of the current situation and of the projects planned in the region regarding wind power, hydrogen production and hydrogen use. Stakeholders involved in, or affected by, the development of the energy infrastructure have been identified. In addition, the report includes a study of the existing and forthcoming regulatory framework in relation to the hydrogen value chain. Moreover, a preliminary techno-economic analysis of a hydrogen gas grid is presented, as well as a SWOT analysis and the consequences for the power grid. Finally, further investigations and research necessary to move forward are suggested.

Hydrogen has been pointed out by the European Union (EU) as a key for reaching carbon neutrality by 2050 (European Commission, 2020b). The key role of hydrogen has also been confirmed by the Swedish Energy Agency, which in November 2021 presented a proposal for a Swedish hydrogen strategy (Swedish Energy Agency, 2021a). To create conditions for a hydrogen energy system, an infrastructure for large scale hydrogen storage and distribution is necessary. This infrastructure could be built in a multitude of ways, e.g. using centralized or de-centralized solutions, and shared versus non-shared infrastructure.

Stakeholder activities in northern Sweden

In some industry branches, fossil-free hydrogen is deemed the best way of achieving industry's climate goals; this is the case for the steel industry. The companies SSAB, LKAB, Vattenfall and H2 Green Steel have taken the lead globally in production of fossil-free steel. Since the establishment of the company HYBRIT Development for fossil-free steel production, more actors such as the ammonia and fertilizer producer Grupo Fertiberia, and energy companies like Uniper and Fortum are making plans for the establishment of hydrogen-intensive industry in northern Sweden. Additionally, several hydrogen refueling stations are planned in the region, and there are plans for heavy-duty-trucks and train operations driven by hydrogen.

Northern Sweden has the synergetic combination of high-grade iron ore and fossil-free electricity. Today, we see many activities and co-operation to support large hydrogen-based industrial investments in the region. For example, the power grid owners are striving to strengthen the power lines for the electricity demand, since there are plans to produce more onshore and offshore wind power, and companies like Nordion Energi are investigating to build hydrogen pipelines to collect the production and needs on a regional level. The Nordic Hydrogen Route (Nordic Hydrogen Route, 2022) is an initiative between Nordion Energi and Gasgrid Finland to create a cross-border hydrogen infrastructure between Sweden and Finland in the Bothnian Bay region. Other supportive actors are national agencies, municipalities, universities, institutes, consultants, NGOs and more, to complete society needs including funding, bringing more skilled people to the region and support the development in general.

Hydrogen has been used in large quantities in industry for over a hundred years. There are both a number of short hydrogen distribution pipelines (e.g. in Sandviken and Stenungsund) in Sweden and long transmission pipelines in a number of locations in full operation in other locations in the world. However, the planned large-scale introduction of production, distribution, storage and use of fossil-free hydrogen in the steel and process industry in northern Sweden is without precedent, especially considering the cold climate in the region.

In order to succeed in the goal of fossil-free production, and the potential this has, a number of obstacles need to be overcome, not least technical. The industries and many actors have begun the work of implementing and supporting the large-scale establishment that is needed, especially energy and wind power companies, and municipalities that need support from a societal perspective. Looking into the future, power supply is expected to be a limiting factor and electricity prices are anticipated to be more volatile, also in the north of Sweden.

Necessary support from national authorities for the introduction of a hydrogen energy system

The use of fossil-free hydrogen in the energy system will lead to greenhouse gas reductions and opportunities for new businesses and more export of sustainable products. Additionally, an increased security of supply will be possible due to local hydrogen production and potential use of energy storage to cover an increased intermittent power production. To reach these targets, further support by authorities will have a large impact on the possibilities to succeed, both on a global level to reach the climate goals, and from a national competition perspective.

In the years to come, governmental activity needs to be higher than today. It is stressed by the partners in the project, that the national strategy as elaborated by the Swedish Energy Agency (Swedish Energy Agency, 2021) should be activated and implemented. That would include actions to facilitate more efficient processes for permits and secure availability of land.

National agencies have important roles to support the hydrogen implementation, e.g. by deciding how a shared hydrogen market should be regulated. Furthermore, incentives to decrease investment risks in early phases are equally important. The roles of municipalities can be supported and coordinated to pave the way for hydrogen pipelines both in terms of land leasing and decision-making in permit processes, as well as the ability to provide support for new business opportunities with locally available hydrogen.

Regulatory framework related to a hydrogen energy system

The existing and forthcoming regulatory framework in related to the hydrogen value chain has been examined. In Swedish legislation, a concession decision, which is needed for the electricity and natural gas transmission grid, gives the holder certain rights and responsibilities and a stronger stance against competing interests. It would be an anomaly if hydrogen pipelines and storages would not need a concession, however, current regulations cannot be directly applied to a hydrogen infrastructure. One solution seems to be to include hydrogen in the Natural Gas Act or to create a new Hydrogen Act. Furthermore, hydrogen activities are not listed in the Environmental Assessment Regulation, which means that no permit obligation exists explicitly, which leaves the operators in the dark regarding what kind of permit process awaits them. The legislator should review this and adapt the existing legislation to include a clear permit obligation for hydrogen activities. Furthermore, the potential need for and requirements on a hydrogen transmission system operator should be investigated.

For power transmission, the main challenge is the transmission capacity of the grid and the long lead times (7–15 years) related to expanding it, although investigations are underway to shorten lead times. For hydrogen transmission, similar challenges can be expected, and possibly even more, since many regulations related to a hydrogen system are lacking and, furthermore, most actors (not the least authorities) have very limited experience from handling expansion of a gas transmission grid, and even less for hydrogen. Hence, in addition to proactively developing the regulations, the lessons that will be learnt regarding processes for expansion of power transmission grid and wind power should be applied when developing similar processes for the hydrogen system.

Sector coupling between the different energy systems will become more common. Hence, the regulation must consider this integration and a close collaboration between authorities and between actors from the different energy systems is necessary. As hydrogen can be used as a flexibility resource, this may help strengthening the interaction between different energy systems. The transition to production of fossil-free steel is, for good reasons, promoted and supported by many actors and the dependence is strong between the hydrogen demand for fossil-free steel and the power supply. However, the social acceptance for new establishments of wind power, to increase the electricity production, is not always strong.

In the EU Taxonomy (European Commission, 2020a), hydrogen produced in electrolysers is considered “sustainable” if emissions from electricity are low enough. Moreover, also hydrogen from fossil fuels with carbon capture and storage (CCS) can be considered “sustainable”, despite emissions that are often at least three times higher than hydrogen from water electrolysis with the Swedish electricity mix. Hydrogen from biomass is another option that can be considered ”sustainable” according to the taxonomy. In the revision of the Renewable Energy Directive, ”renewable” hydrogen will be defined, and the requirements suggested are significantly higher than for “sustainable” hydrogen. Only hydrogen from water electrolysis is considered “renewable”, but not hydrogen from fossil gas, nor from biomass or biogas, and in addition, electricity production must meet strict requirements. The choice of definition that will set the limit to be eligible for public support could have large effects on the development of the hydrogen system and, hence, would benefit from thorough discussions and investigations, both at national and EU level. Hence, Swedish stakeholders, including authorities and government, could benefit from taking a more active role to include the unique perspective of northern Sweden in the forthcoming regulative frameworks.

Several gaps in current legislation with regards to the hydrogen system have been found. Despite the many uncertainties, the interest from industrial actors to develop hydrogen activities is huge. Hence, to reduce investment uncertainties and facilitate the desired development, a more thorough investigation and development of legislation related to the hydrogen system is recommended, e.g. a Swedish Government Official Report (SOU) or a national coordinator for authorities handling permits related to the hydrogen energy system. Furthermore, a national strategy for hydrogen, based on the current proposal, should be developed. However, there is also a need to consider if some issues should be prioritized and investigated in short-term, e.g. a revision of the Natural Gas Act to include concession and TSO for hydrogen pipelines. Thus, in addition to more thorough investigations, each actor needs to consider which issues they could improve to enable a fossil-free hydrogen system.

Preliminary techno-economic assessments

Two different scenarios have been created describing radically different ways to supply the future demand of hydrogen in the northern electricity market zone in Sweden (SE1). In one scenario (A), the region’s complete hydrogen demand was assumed to be produced via electrolysis at each of the industrial sites. In the other scenario (B), the complete hydrogen demand was assumed to be supplied via a hydrogen pipeline. **Both these scenarios should be considered as thought experiments and not an attempt to reflect the future reality.** It is also important to understand that the scenarios are not directly comparable to each other. The two supply systems are complex and during this prestudy many assumptions and simplifications had to be made in each of the scenarios, leading to difficulties to make fair comparisons. Therefore, the main aim of the techno-economic assessment has been to learn about their respective technical and economic characteristics, opportunities, and potential drawbacks.

One important learning was that, despite the dramatic electricity demand increase that is foreseen in the region (50% increase between the years 2020 and 2030), it seems likely that there will be enough renewable power production in the region studied to fulfil the future demands for both hydrogen and electricity. This is to a large extent dependent on that the massive plans for new wind power investments (>100 TWh per year) on the Finnish side of the region are realised, and that this electricity is available for use in SE1. The renewable power production planned in SE1 alone does not cover the demand foreseen by the industry.

To realise this power production potential, vast infrastructure investments are needed. In Scenario A, the transmission capacity between Finland and Sweden must be enlarged by around three times to cope with the required imports to Sweden in 2030. In Scenario B, a hydrogen pipeline along the Gulf of Bothnia must be built to be able to transmit large volumes of hydrogen produced on the Finnish side, mainly for use in Sweden. It can be concluded that the costs for hydrogen production and storage are the dominating posts in both scenarios, while the cost for the transmission, using power grid or hydrogen pipeline, are marginal. The costs for hydrogen production are to a large extent dependent on the electricity cost for the electrolysers. Hence, it is important to be able to benefit from low-cost electricity, e.g. by using flexible operation of the electrolysers and low-cost wind power.

Several important technical benefits were identified with a hydrogen pipeline system, such as mild land use impact and good opportunities to coordinate with other infrastructure investments. In the stakeholder interviews, it was also brought up the potential positive impacts on development of municipalities along the pipeline, such as hydrogen off-take hubs that could attract new businesses in the region.

However, even with a pipeline system supplying the complete demand of hydrogen, the existing power grid to areas of Kiruna, Gällivare, and Luleå is likely insufficient to supply the power demand. The power grid of these areas may therefore need to be strengthened. It was further shown how the current revision of the Renewable Energy Directive could have a substantial influence on required infrastructure investments.

It is evident that power and hydrogen transmission can complement each other in an energy- and cost-efficient way. The main conclusion is therefore that great and fast efforts should be put on developing a hybrid system to avoid unnecessary lock-in effects. This prestudy has paved the way for such efforts.

Research questions for further work

The outlining of further work is designed to support and accelerate the industrial developments that are on-going in northern Sweden. General research on components (e.g. electrolysers) is not included in the outline of this report, assuming that this is already addressed in other research programs that are supported by various agencies in Sweden and the EU.

In the project interviews with the stakeholders, the difficulty for companies and organisations to find relevant competence has been identified as a serious obstacle for the development. It is therefore important to develop a variety of different educational programs, aimed at university level engineers, current staff in the companies (life-long learning) and people from other industry sectors that want to change sector (up-skilling and re-skilling). There is also a need for education and information to public servants, politicians and members of the public who need to or want to learn more.

Regulatory work is another important area that needs attention. Regulatory work means the development of laws, rules and standards that are necessary for the protection of third parties and for defining a level playing field for industrial actors.

The needs for research and development connected to large-scale hydrogen systems in cold climates are multi-facetted. There is a need for additional system analysis to increase the understanding of a new energy system in northern Sweden and Finland (and elsewhere) where hydrogen pipelines are a central part. This will provide valuable input for decisions about the pipeline network design and the dimensioning of the combined electricity and hydrogen system. There is also a need for fluid dynamics research aimed at improving the understanding of transients in the system. Lined rock cavern storage is the main candidate for large scale storage in the region but there is a lack of scientifically based design of such structures that can account for real rock with cracks and other stochastic imperfections. There is also a need for material science research, both for metallic and polymer materials, related to large scale pipelines and hydrogen storage in cold climates. The safety of largescale systems is another important research area.

The investments in fossil-free industry and hydrogen infrastructure will require large electrolyser systems with hundreds of multi-MW-scale electrolyser stacks that are feeding into the hydrogen distribution system. There are several potential problems connected to these installations that must be investigated and addressed. One issue is to find an optimal solution for the conflicting goals of having sufficient ventilation to prevent potential leaks from creating a flammable mixture and to minimize the costs for heating and ventilation.

Large hydrogen systems will create challenges but will also provide solutions with respect to the total energy system. It is a challenge that there will be a need for a significant increase in the total power production. However, the new hybrid power and hydrogen system has a different dynamic than the present power system. In the new hybrid system, it will be possible to rapidly reduce the power demand for the electrolysers in the region if there is enough stored hydrogen available. The disconnection of load has an equivalent impact to the power system as the connection of equally large power generators. The effect from such disconnection and other large contingencies on the stability and power quality needs to be studied from a power systems perspective since this might ultimately damage sensitive equipment connected to the grid. Another question is how to design well-functioning System Integrity Protection Schemes (SIPS) that can increase the resilience of the grid to cope with large additions of weather dependent power generators and increase the transmission capacity through utilisation of available assets.

There is a limit for the efficiency of electrolysers, typically around 70%, and this will result in significant amounts of waste heat that has a potential value. Another by-product from the electrolysers is large amounts of oxygen. These waste products will not drive the business, but they can still provide an added value if properly utilised. However, more research and development are needed before the potential can be fully utilized.

The creation of a combined hydrogen and power grid will lead to a new business situation. To exploit this to the fullest, seen both from a society and an industry perspective, there is a need for additional market design research aimed at developing an efficient hydrogen market. Some of the subtasks in this research are to identify actors and the potential for market abuse. Also, the best way to provide flexibility to the power grid and the impact from this on the power grid is an important subtask. Based on these investigations it would be possible to find a preferred design of a hydrogen marketplace.

Furthermore, social acceptance will be an important factor for the rapid deployment of the hydrogen system and the development of the new power generation that will be needed to produce enough hydrogen. However, in the current situation, there is much that indicate that the general public is sceptic to more wind power and also to the introduction of hydrogen in the energy system. To remedy this situation, public education will be one important activity but there is also a need for finding ways of creating financial incentives to accept the changes for the local communities that are affected by the development. Connected to this need, there is a need for social science research, similar to the existing lines of inquiry about the opening of new mines and wind farms.

A draft collection of activities is presented at the end of the report. These activities have been designed to harmonise with the proposal for a Swedish hydrogen strategy (Energimyndigheten, 2021). The activities have been divided in four suggested areas to achieve the goals of the strategy:

1. Research, innovation and competence.
2. Co-operation for a developed value chain.
3. Development of frameworks and regulations.
4. Economic incentives.

Sammanfattning

Denna förstudie har genomförts av RISE Research Institute of Sweden och Luleå tekniska universitet tillsammans med ytterligare 24 intressenter inom energisystem med vätgas i norra Sverige (i detta fall Norrbottens och Västerbottens län). Studien finansierades av Vinnova och de deltagande organisationerna.

Syftet med denna rapport är att analysera förutsättningar, möjligheter och hinder för utvecklingen av en vätgasinfrastruktur i norra Skandinavien och Finland. Målet är att ge en uppdaterad bild av nuläget och av de projekt som planeras i regionen avseende vindkraft, vätgasproduktion och vätgas-användning. Aktörer som är involverade i eller påverkas av utvecklingen av energiinfrastrukturen har identifierats, och det befintliga och kommande regelverket i relation till värdekedjan för vätgas har summerats. Vidare har en tekno-ekonomisk analys av vätgas-pipelines och konsekvenserna för elnätet genomförts, samt SWOT-analyser för de olika alternativen. Slutligen har ytterligare undersökningar och forskning som krävs för att komma vidare mot ett energisystem med vätgas föreslagits.

Vätgas har av Europeiska unionen (EU) pekats ut som en nyckel för att uppnå koldioxidneutralitet till 2050 (European Commission, 2020b). Vätgasens nyckelroll har också bekräftats av Energimyndigheten som i november 2021 presenterade ett förslag till en svensk vätgasstrategi (Swedish Energy Agency, 2021a). För att skapa förutsättningar för ett energisystem med vätgas behövs en infrastruktur för storskalig vätgaslagring och distribution. Denna infrastruktur kan byggas på flera olika sätt, exempelvis genom centraliserade eller de-centraliserade lösningar, och delad eller icke-delad infrastruktur.

Aktiviteter bland intressenter i norra Sverige

Inom vissa branscher anses fossilfri vätgas vara det bästa sättet att uppnå industrins klimatmål; detta är fallet för stålindustrin. Företagen SSAB, LKAB, Vattenfall och H2 Green Steel har tagit täten globalt inom produktion av fossilfritt stål. Sedan etableringen av företaget HYBRIT Development för fossilfri stålproduktion planerar fler aktörer som ammoniak- och gödselproducenten Grupo Fertiberia, och energibolag som Uniper och Fortum för etablering av vätgasintensiv industri i norra Sverige. Dessutom planeras flera tankstationer för vätgas i regionen, och det finns planer på tunga lastbilar och tågdrift med vätgas.

Norra Sverige har kombinationen av högvärdig järnmalm och fossilfri el som möjliggör de stora satsningar på vätgasbaserade industriinvesteringar i regionen. Exempelvis arbetar elnätsägarna med att stärka kraftledningarna för att möta planer på att producera mer land- och havsbaserad vindkraft, och företag som Nordion Energi utreder att bygga vätgasledningar för att samla produktionen och behoven på en regional nivå. Nordic Hydrogen Route (Nordic Hydrogen Route, 2022) är ett initiativ mellan Nordion Energi och Gasgrid Finland för att skapa en gränsöverskridande vätgasinfrastruktur mellan Sverige och Finland i Bottenviken. Andra aktörer som stödjer utvecklingen är nationella myndigheter, kommuner, universitet, institut, konsulter, och icke-statliga organisationer; dessa arbetar med att fylla samhällets behov inklusive finansiering och att locka fler människor till regionen.

Vätgas har använts i stora mängder inom industrin i över hundra år. Det finns både ett antal korta distributionsledningar (t.ex. i Sandviken och Stenungsund i Sverige) och långa transmissionsledningar på ett antal platser i världen. Dock saknar det planerade storskaliga införandet av produktion, distribution och användning av fossilfritt väte i stål- och processindustrin i norra Sverige motstycke, särskilt med tanke på det kalla klimatet i regionen.

För att lyckas med målet om fossilfri industri och den potential detta har, behöver en rad hinder övervinnas, inte minst tekniska. Branscherna och många aktörer har påbörjat arbetet med att implementera och stödja den storskaliga etablering som behövs, framför allt energi- och vindkraftsföretag samt kommuner som behöver stöd ur ett samhällsperspektiv. Sett in i framtiden förväntas elförsörjningen vara en begränsande faktor och elpriserna förväntas bli mer volatila, även i norra Sverige.

Nödvändigt stöd från myndigheter för införing av ett energisystem med vätgas

Användningen av fossilfri vätgas i energisystemet kommer att leda till minskningar av växthusgaser och möjligheter för nya företag och mer export av hållbara produkter. Dessutom kommer en ökad försörjningstrygghet att vara möjlig på grund av lokal vätgasproduktion och potentiell användning av energilagring för att täcka en ökad intermittent kraftproduktion. För att nå dessa fördelar kommer ytterligare stöd från myndigheter att ha stor betydelse för möjligheterna att lyckas, både på global nivå för att nå klimatmålen, och ur ett nationellt konkurrensperspektiv.

Under de kommande åren behöver den statliga aktiviteten vara högre än idag. Det framhålls av partnerna i projektet att den nationella strategin som utarbetats av Energimyndigheten (Energimyndigheten, 2021) bör aktiveras och implementeras. Det skulle innefatta åtgärder för att underlätta effektivare processer för tillstånd och säker tillgång till mark.

Nationella myndigheter har viktiga roller för att stödja vätgasimplementeringen, t.ex. genom att bestämma hur en delad vätgasmarknad ska regleras. Dessutom är incitament att minska investeringsriskerna i tidiga faser lika viktiga. Kommunernas roller kan stödjas och samordnas för att bana väg för vätgasledningar både vad gäller markupplåtelse och beslutsfattande i tillståndsprocesser, samt möjligheten att ge stöd till nya affärsmöjligheter med lokalt tillgänglig vätgas.

Regleringar relaterade till ett energisystem med vätgas

Det existerande och kommande regelverket relaterat till en värdekedja för vätgas har undersökts. I svensk lagstiftning ger ett koncessionsbeslut, som behövs för el- och naturgasöverföringsnätet, innehavaren vissa rättigheter och skyldigheter och en starkare ställning mot konkurrerande intressen. Det skulle vara en anomali om vätgasledningar och lager inte skulle behöva en koncession, men nuvarande regler kan inte tillämpas direkt på en vätgasinfrastruktur. En lösning skulle kunna vara att ta in vätgas i naturgaslagen eller att skapa en ny vätgaslag. Vidare finns inte vätgasverksamheter listade i miljöprövningsförordningen, vilket innebär att det inte finns någon uttryckt tillståndsplikt, vilket lämnar verksamhetsutövarna i limbo om vilken typ av tillståndsprocess som väntar dem. Lagstiftaren bör se över detta och anpassa den befintliga lagstiftningen så att den innehåller en tydlig tillståndsplikt för vätgasverksamhet. Vidare bör det potentiella behovet av och kraven på en systemansvarig för vätgasöverföring utredas.

För kraftöverföring är den största utmaningen i samband med utbyggnad av nätets överförings-kapacitet och de långa ledtiderna (7–15 år) för utbyggnad, även om utredningar pågår för att korta ledtiderna. För vätgasöverföring kan liknande utmaningar förväntas, och möjligen ännu fler, eftersom många regleringar relaterade till ett vätgassystem saknas och dessutom har de flesta aktörer (inte minst myndigheter) begränsad erfarenhet av att hantera utbyggnad av ett gasöverföringsnät. Och ännu mindre för vätgas. Därför bör, förutom ett proaktivt utvecklande av regelverket, lärdomar om processer från utbyggnad av kraftöverföringsnät och vindkraft användas vid utveckling av liknande processer för vätgassystemet.

Sektorskoppling mellan olika energisystem kommer att bli vanligare framöver. Därför måste regelverken beakta denna integration och det är nödvändigt med ett nära samarbete mellan myndigheter och mellan aktörer inom de olika energisystemen. Eftersom vätgas kan användas som en flexibilitetsresurs kan detta bidra till att stärka samspelet mellan olika energisystem. Omställningen till produktion av fossilfritt stål uppmuntras och stöds, av goda skäl, av många aktörer och beroendet är stort mellan vätgasefterfrågan och tillgång till förnybar el; dock är den sociala acceptansen för nyetableringar av vindkraft inte alltid stark.

Inom EU-taxonomin (European Commission, 2020a) anses vätgas som produceras i elektrolysörer vara ”hållbar” (*sustainable*) om utsläppen från el är tillräckligt låga. Dessutom kan även vägas från fossila bränslen med koldioxidinfångning (*carbon capture and storage*, CCS) betraktas som ”hållbart”, trots utsläpp som ofta är minst tre gånger högre än vätgas från den svenska elmixen. Vätgas från biomassa är ett annat alternativ som kan anses vara ”hållbart” enligt taxonomin. I översynen av direktivet för förnyelsebar energi (*Renewable Energy Directive*, RED) kommer

”förnybar” (*renewable*) vätgas att definieras, och de föreslagna kraven är betydligt högre än för ”hållbar” vätgas. Endast vätgas från elektrolysörer anses här vara ”förnybart”, men inte vätgas framställd från fossil gas, inte heller från biomassa eller biogas, och dessutom behöver elproduktionen uppfylla hårda krav. Valet av definition, som bestämmer vilken vätgasproduktion som är berättigad till offentligt stöd, kan få stora effekter på utvecklingen av vätgassystemet och skulle därför gynnas av grundliga diskussioner och utredningar, både på nationell nivå och på EU-nivå. Därför skulle svenska intressenter, inklusive myndigheter och regering, kunna dra nytta av att ta en mer aktiv roll för att inkludera norra Sveriges unika perspektiv i de kommande regelverken.

Flera luckor i gällande lagstiftning när det gäller vätgassystemet har upptäckts. Trots de många osäkerheterna är intresset från industriella aktörer att utveckla vätgasverksamhet enormt. För att minska investeringsosäkerheten samt underlätta den önskade utvecklingen och med tanke på de potentiellt stora effekterna på hela energisystemet och övergången till fossilfritt stål rekommenderas därför en grundlig utredning av lagstiftningen kring vätgassystemet. Det bör dock också övervägas om vissa frågor också behöver prioriteras och utredas på kort sikt, t.ex. behovet av koncession.

Preliminära teknoekonomiska analyser

Två olika scenarier har skapats som beskriver radikalt olika sätt att tillgodose den framtida efterfrågan på vätgas i det nordligaste elområdet i Sverige (SE1). I ett scenario (A) antogs regionens fullständiga vätgasbehov produceras via elektrolys vid var och en av industrianläggningarna. I det andra (B) antogs det fullständiga vätgasbehovet tillgodoses via en vätgasledning. **Båda dessa scenarier bör betraktas som tankeexperiment och inte ett försök att spegla den framtida verkligheten.** Det är också viktigt att förstå att scenarierna inte är direkt jämförbara med varandra. De två försörjningssystemen är komplexa och under denna förstudie måste många antaganden och förenklingar göras i vart och ett av scenarierna, vilket ledde till svårigheter att göra rättvisa jämförelser. Därför har huvudsyftet med den teknoekonomiska bedömningen varit att lära sig om deras respektive tekniska och ekonomiska egenskaper, möjligheter och potentiella nackdelar.

En viktig lärdom var att, trots den dramatiska ökningen av energibehovet som förutses i regionen (50 % ökning mellan år 2020 och 2030), verkar det troligt att det kommer att finnas tillräckligt med förnybar kraftproduktion i den studerade regionen för att uppfylla de framtida kraven för både vätgas och el. Detta är till stor del beroende av att de massiva planerna för nya vindkraftsinvesteringar (>100 TWh per år) på den finska sidan av regionen förverkligas, och att denna el är tillgänglig för SE1. Planerna på förnybar elproduktion i SE1 är inte tillräckliga för att täcka behoven som förutspås i de industriella satsningarna.

För att utnyttja denna produktionspotential krävs stora infrastrukturinvesteringar. I scenario A måste överföringskapaciteten mellan Finland och Sverige utökas med cirka tre gånger för att klara av den import som krävs till Sverige år 2030. I scenario B måste en vätgasledning byggas utmed Bottenviken för att kunna överföra stora volymer vätgas som produceras på den finska sidan, främst för användning i Sverige. En slutsats som kan dras är att kostnaderna för vätgasproduktion och lagring är de dominerande posterna i båda scenarierna, medan kostnaden för överföring med kraftnät eller vätgasledning är marginell. Kostnaderna för vätgasproduktion är till stor del beroende av elkostnaden för elektrolysörerna. Därför är det viktigt att kunna dra fördel av billig el, t.ex. genom att utnyttja flexibel drift av elektrolysörerna och lågkostnadsel från vindkraft.

Flera viktiga tekniska fördelar identifierades med ett vätgasledningssystem, såsom mild mark-användningspåverkan och goda möjligheter att samordna med andra infrastrukturinvesteringar. Från intressentintervjuerna togs det också upp de potentiella positiva effekterna på utvecklingen av kommuner längs en eventuell vätgasledning, såsom knutpunkter för vätgasuttag som kan locka nya företag i regionen.

Men även med ett rörledningssystem som tillgodoser hela efterfrågan av vätgas är det befintliga kraftöverföringsnätet till områdena Kiruna, Gällivare och Luleå sannolikt otillräckligt för att tillgodose kraftbehovet. Dessa områdens kraftdistributionsnät kan därför behöva förstärkas. Det visades vidare hur den nuvarande revisionen av direktivet om förnybar energi (RED) skulle kunna få stort inflytande på nödvändiga infrastrukturinvesteringar.

Det är tydligt att elnät och vätgasledningar kan komplettera varandra på ett energi- och kostnadseffektivt sätt. Huvudslutsatsen är därför att stora och snabba satsningar bör fokuseras på att utveckla ett hybridsystem för att undvika onödiga inlåsningseffekter. Detta förstudieprojekt har banat väg för sådana satsningar.

Forskningsfrågor för framtida arbete

Utformningen av det fortsatta arbetet syftar till att stödja och påskynda den industriella utveckling som pågår i norra Sverige. Allmän forskning om komponenter (t.ex. elektrolysörer) ingår inte i denna rapport, eftersom detta redan behandlas i andra forskningsprogram som stöds av olika organ i Sverige och EU.

I projektets intervjuer med intressenterna har svårigheten för företag och organisationer att hitta relevant kompetens identifierats som ett allvarligt hinder för utvecklingen. Det är därför viktigt att utveckla en rad olika utbildningsprogram, som riktar sig till ingenjörer på universitetsnivå, nuvarande personal i företagen (livslångt lärande) och personer från andra industrisektorer som vill byta sektor (upp- och omskolning). Det finns också ett behov av utbildning och information till tjänstemän, politiker och allmänheten som behöver eller vill lära sig mer.

Ett annat viktigt område är utveckling av lagar, regler och standarder som är nödvändiga för att skydda tredje part och för att skapa lika villkor för näringslivets aktörer.

Behoven av forskning och utveckling i samband med storskaliga vätgassystem i kallt klimat är mångfacetterade. Det finns ett behov av ytterligare systemanalyser för att öka förståelsen för ett nytt energisystem i norra Sverige och Finland (och på andra håll) där vätgasledningar är en central del. Detta kommer att ge värdefullt underlag för beslut om utformningen av rörledningsnätet och dimensioneringen av det kombinerade el- och vätgassystemet. Det finns också ett behov av flödesdynamisk forskning som syftar till att förbättra förståelsen av transienter i systemet. Lagring i bergrum är den viktigaste kandidaten för storskalig lagring i regionen, men det saknas en vetenskapligt grundad utformning av sådana strukturer som kan ta hänsyn till verkliga bergarter med sprickor och andra stokastiska inhomogeniteter. Det finns också ett behov av materialvetenskaplig forskning, både när det gäller metalliska och polymera material, i samband med storskaliga rörledningar och vätgaslagring i kallt klimat. Säkerheten hos storskaliga system är ett annat viktigt forskningsområde.

Investeringarna i fossilfri industri och infrastruktur för vätgas kommer att kräva stora elektrolys-system med hundratals elektrolysör-stackar i multi-MW-skala som matas in i vätgasnätet. Det finns flera potentiella problem i samband med dessa installationer som måste undersökas och åtgärdas. Ett problem är att hitta en optimal lösning för de motstridiga målen att förhindra att potentiella läckor skapar en brandfarlig blandning och att minimera kostnaderna för uppvärmning och ventilation.

Stora vätgassystem kommer att skapa utmaningar, men kommer också att erbjuda lösningar med avseende på det totala energisystemet. Det är en utmaning att det kommer att behövas en betydande ökning av den totala elproduktionen. Dock har det nya hybridsystemet med el och vätgas en annan dynamik än det nuvarande elsystemet. I det nya hybridsystemet kommer det att vara möjligt att koppla bort alla elektrolysörer i regionen från kraftsystemet om det finns tillräckligt med lagrad vätgas. Att koppla bort belastningen har en likvärdig inverkan på kraftsystemet som att koppla in lika stora kraftgeneratorer. Effekten av en sådan bortkoppling och andra stora oförutsedda händelser på stabiliteten och elkvaliteten måste studeras ur ett kraftsystemperspektiv, eftersom detta i slutändan kan skada känslig utrustning som är ansluten till nätet. En annan fråga är hur man kan utforma väl fungerande systemintegritetsskyddssystem (SIPS) som kan öka nätets motståndskraft för att klara av stora tillskott av väderberoende kraftgeneratorer och öka överföringskapaciteten genom att utnyttja tillgängliga resurser.

Det finns en gräns för elektrolysörernas effektivitet, vanligtvis omkring 70 %, och detta kommer att tillgängliggöra betydande mängder spillvärme som har ett potentiellt värde. En annan biprodukt från elektrolysörerna är stora mängder syre. Dessa avfallsprodukter kommer inte att driva den ekonomiska lönsamheten, men de kan ändå ge ett mervärde om de utnyttjas på rätt sätt. Det krävs dock mer forskning och utveckling innan potentialen kan utnyttjas fullt ut.

Skapandet av ett kombinerat vätgas- och elnät kommer att leda till en ny affärssituation. För att utnyttja detta till fullo, sett både ur ett samhälls- och industriperspektiv, behövs ytterligare forskning om marknadsutformning som syftar till att utveckla en effektiv vätgasmarknad. Några av deluppgifterna i denna forskning är att kartlägga aktörer och potentialen för marknadsmissbruk. En viktig deluppgift är också hur man på bästa sätt kan skapa flexibilitet i elnätet och hur detta påverkar elnätet. På grundval av dessa undersökningar skulle det vara möjligt att hitta en önskad utformning av en vätgasmarknad.

Vidare kommer samhällets acceptans att vara en viktig faktor för en snabb utbyggnad av vätgassystemet och för utvecklingen av den nya kraftproduktion som kommer att behövas för att producera tillräckligt med vätgas. I dagsläget finns det dock mycket som tyder på att allmänheten är skeptisk till mer vindkraft och även till införandet av vätgas i energisystemet. För att råda bot på denna situation kommer tillhandahållande av objektiva fakta till allmänheten att vara en viktig åtgärd, men det finns också ett behov av att hitta sätt att skapa ekonomiska incitament för allmänheten att acceptera den påverkan av lokalsamhällen som kommer att ske. I anslutning till detta behov finns det ett behov av samhällsvetenskaplig forskning, i likhet med de befintliga undersökningarna om öppnandet av nya gruvor och vindkraftverk.

Ett utkast till en samling aktiviteter presenteras i slutet av rapporten. Dessa aktiviteter har utformats för att harmonisera med förslaget till en svensk vätgasstrategi (Energimyndigheten, 2021). Aktiviteterna har delats in i fyra föreslagna områden för att uppnå strategins mål:

1. Forskning, innovation och kompetens.
2. Samarbete för en utvecklad värdekedja.
3. Utveckling av ramar och bestämmelser.
4. Ekonomiska incitament.

Nomenclature

Blue hydrogen	Hydrogen produced from natural gas applying CCS.
CAPEX	Capital expenditures, or investment costs. Money used by an organisation to purchase, improve, or sustain physical assets.
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CHP	Combined Heat and Power production
Distribution pipelines	Distribution of hydrogen for shorter distances, typically at lower pressures than transmission pipelines.
EU	European Union
Green hydrogen	Hydrogen produced by electrolysis using renewable electricity.
LMA2021	The long-term market analysis from Svenska Kraftnät in 2021.
OPEX	Operational expenditures, costs incurred in a company during normal business operation. Includes e.g. costs for electricity, maintenance and raw materials.
Power-to-X	Power-to-X (also *Power-2-X or P2X*) includes a number of electricity conversion, energy storage, and reconversion pathways that use surplus electric power, typically during periods where fluctuating renewable energy generation exceeds load. Power-to-X conversion technologies allow for the decoupling of power from the electricity sector for use in other sectors (such as transport or chemicals).
PPA	Power Purchase Agreement, a contractual agreement between electricity buyers and sellers.
RE	Renewable Energy
SE1–SE4	The four electricity market bidding zones[1] in Sweden.
SME	Small and Medium-sized Enterprise
SvK	Svenska kraftnät is the Swedish TSO for electrical power, i.e. Svenska kraftnät maintains and develops the Swedish national grid for electricity.
TSO	Transmission System Operator
Transmission pipelines	Transmission of hydrogen for longer distances, typically at higher pressures than distribution pipelines.

[1] https://www.nordpoolgroup.com/en/the-power-market/Bidding-areas/

Table of contents

1 Introduction

The purpose of this report is to analyse the conditions, opportunities, and obstacles for the development of a hydrogen infrastructure in northern Scandinavia and Finland. In Chapter 2, an updated picture of the current situation and of the projects planned in the region regarding wind power, hydrogen production and hydrogen use is presented. Stakeholders involved in, or affected by, the development of the energy infrastructure have been identified. In Chapter 3, a study of the existing and forthcoming regulatory framework in relation to the hydrogen value chain is presented. In Chapter 4, a preliminary techno-economic analysis of a hydrogen gas grid is conducted, as well as a SWOT analysis and the consequences for the power grid. Finally, further investigations and research necessary to move forward have been suggested in Chapter 5.

1.1 Background: fossil-free industry using hydrogen

Hydrogen has been pointed out by the EU as a key for reaching carbon neutrality by 2050 (European Commission, 2020b). The key role of hydrogen has also been confirmed by the Swedish Energy Agency, which in November 2021 presented a proposal for a Swedish hydrogen strategy (Swedish Energy Agency, 2021a). The proposal is to a large degree based on the steel industry's needs for hydrogen as the only solution identified to achieve their climate goals. However, there is also great interest in fossil-free hydrogen from other industries, e.g. the fertilizer and ammonia industrial sectors.

Hydrogen has been used in large quantities in industry for over a hundred years. There are both a number of short hydrogen distribution pipelines (e.g. in Sandviken and Stenungsund) in Sweden and long transmission pipelines in a number of locations in full operation in other locations in the world. However, the planned large-scale introduction of production, distribution, storage and use of fossil-free hydrogen in the steel and process industry in northern Sweden is without precedent, especially considering the cold climate in the region.

According to the Global Hydrogen Review 2022 (IEA, 2022), many new key applications for hydrogen are showing signs of progress in several countries. The first hydrogen fuel cell train started operating in Germany in 2018 (The Global Energy Association, 2020). There are also more than 100 pilot and demonstration projects for using hydrogen and its derivatives in shipping, and major companies are already signing strategic partnerships to secure the supply of these fuels. There are also hydrogen-related activities in other parts of Sweden, which are not covered in this report. For example, in the Stenungsund area, there are increased future need of hydrogen due to plans to produce electrofuels and a switch from fossil to bio-based raw materials. In general, this increases the demand for hydrogen (Edvall et al., 2022). Moreover, there are at present four hydrogen fueling stations in Sweden, and around 40 more have been publicly announced (Energigas Sverige, 2022).

The hydrogen used in the industrial processes should be produced in such a way that it does not contribute to the emission of greenhouse gases. In the Norrbotten region, the most interesting carbon neutral method is to produce the hydrogen by water electrolysis, using fossil-free electricity. Norrbotten already has a large fossil-free power production and a strong power grid. However, the demand for new power and hydrogen production is so large that it will be difficult to meet it only using local production. On the other hand, Finland has extensive plans for building new wind power that could be used for electrolysis. In addition, a new low-carbon footprint nuclear power plant recently came on-line, which will be an important asset for stabilising the power grid when more wind power is added.

More than 85% of the EU iron ore production comes from the county of Norrbotten, Sweden[1]. The large interest in fossil-free steel from customers to the steel industry has motivated the iron and steel companies in Norrbotten to formulate aggressive plans for large-scale implementation of fossil-free

[1] https://www.at-minerals.com/en/artikel/at_Metal_ore_mining_in_Europe_3257608.html

iron and steel making. If these plans are realised, they would lead to a very large demand for fossil-free hydrogen, that could either be produced by the industry themselves or by independent parties.

1.2 Research questions: Power grid and hydrogen pipelines

An important question in connection to the expected transformation to a fossil-free industry and energy system is whether the hydrogen production should be done locally at the industry end-user sites, or whether the hydrogen production should be distributed in the power grid and transported in pipelines to the end-users. Both alternatives require great investments and substantially increase the demand for electricity. Other important parameters to consider are that the alternatives will require different amounts of land use and underground/underwater transport, and both alternatives imply different amounts of losses during the transport of hydrogen and power. There are more parameters that complicate the picture and that makes it difficult to select the best commercial and sustainable solutions. Some of these parameters are elaborated in this prestudy and some are suggested for further work.

1.3 Geographic system boundary of the study

The present study has analysed the conditions, opportunities, and obstacles for the development of a hydrogen infrastructure in northern Scandinavia and Finland. The focus of the report is around a northern Swedish[1] context, but the report also includes mapping of the development in northern Norway and Finland. During the project, we have had close contact with representatives from VTT on the Finnish side of the Gulf of Bothnia. Additionally, interviews performed by Business Sweden have mapped stakeholders and investments planned in Norway and Finland, and the preliminary techno-economic assessments include data for windmills and hydrogen production in Finland. A prestudy similar to the present one has been started by VTT (Lehtonen & Kärki, 2022; Yle, 2022) that is expected to be finished in the beginning of 2023. That study will use data from the present prestudy to further strengthen the overview of the research area in the region.

[1] More specifically Norrbotten County and Västerbotten County, the two northern-most counties of Sweden.

2 Current development towards a hydrogen energy system

This chapter summarises outputs from interviews and discussions within the project consortium during the project. The sub chapters describe key actors and planned investments in northern Sweden, Norway and Finland.

2.1 Mapping of actors in northern Sweden, Finland and Norway

In northern Sweden, the hydrogen development is largely driven by the mining and steel industry where hydrogen will replace coal for conversion of iron ore and by companies aiming at producing sustainable synthetic fuels and chemicals. In Norway, production of synthetic fuels like methanol and ammonia is an important driver where hydrogen development is largely shaped by the petroleum and maritime sector. In Finland, hydrogen has until today been used for mainly oil refining, biofuels production and in the chemical industry. For the future, the main focus is various Power-to-X solutions for production of synthetic fuels. Power-to-X conversion technologies allow for the decoupling of power from the electricity sector for use in other sectors, such as transport or chemicals.

There are a number of actors such as industry companies, universities, research organisations, communities and regions that are active in the hydrogen area or are planning for activities in the future. Some of the key stakeholders for northern Sweden, Norway and Finland can be found in Appendix 1. For northern Sweden, the stakeholders have been identified using the project consortium, both from interviews and other discussions during the project. For Norway and Finland, the stakeholders have been mapped by the project partner Business Sweden. The methodology of Business Sweden was to first gather background information on current hydrogen developments in Norway and Finland and then to conduct interviews with some of the key industry organisations.

2.1.1 Stakeholders and investments in northern Sweden

In November 2021, the Swedish Energy Agency presented a proposal for a Swedish hydrogen strategy (Swedish Energy Agency, 2021a). In some industry branches, fossil-free hydrogen is deemed the best way of achieving industry's climate goals; this is the case for the steel industry. The companies SSAB, LKAB, Vattenfall and H2 Green Steel have taken the lead globally in production of fossil-free steel. Since the establishment of the company HYBRIT Development for fossil-free steel production, more actors such as the ammonia and fertilizer producer Grupo Fertiberia, and energy companies like Uniper and Fortum are making plans for the establishment of hydrogen-intensive industry in northern Sweden. Additionally, several hydrogen refuelling stations are planned in the region, and there are plans for heavy-duty-trucks and train operations driven by hydrogen. Furthermore, there are plans to use hydrogen to produce synthetic fuels combined with carbon capture in many locations in the north by several stakeholders, or other hydrogen-based products.

Northern Sweden has the synergetic combination of high-grade iron ore and fossil-free electricity. Today, we see many activities and co-operation to support large hydrogen-based industrial investments in the region. For example, the power grid owners are striving to strengthen the power lines for the electricity demand, since there are plans to produce more onshore and offshore wind power, and companies like Nordion Energi are investigating to build hydrogen pipelines to collect the production and needs on a regional level. The Nordic Hydrogen Route (Nordic Hydrogen Route, 2022) is an initiative between Nordion Energi and Gasgrid Finland to create a cross-border hydrogen infrastructure between Sweden and Finland in the Bothnian Bay region. Nordion is also part of the European Hydrogen Backbone initiative (van Rossum et al., 2022) that is contributing to the development of a European hydrogen market. Other supportive actors are national agencies, municipalities, universities, institutes, consultants, NGOs and more, to complete society needs including funding, bringing more skilled people to the region and support the development in general.

Hydrogen has been used in large quantities in industry for over a hundred years. There are both a number of short hydrogen distribution pipelines (e.g. in Sandviken and Stenungsund) in Sweden and long transmission pipelines in a number of locations in full operation in other locations in the world.

However, the planned large-scale introduction of production, distribution, storage and use of fossil-free hydrogen in the steel and process industry in northern Sweden is without precedent, especially considering the cold climate in the region.

In the first part of this prestudy, the consortium members were interviewed regarding their present and future role within the hydrogen scope. As illustrated in Table 1, many of the stakeholders are investigating several parts of the value chain. Companies that traditionally only have been present in a limited field, tends to move and act in multiple areas. This will change the industrial landscape. For example; energy companies move towards chemicals production and steel companies become energy producers etc. So, instead of acting in only their own traditional area, many companies now become a part of an ecosystem.

In order to build a hydrogen market, all actors need to collaborate and participate in the build-up of the value chain. It is stated by many of the consortium members that “We must do this together”. No one can build an ecosystem alone.

Table 1. Mapping some of the stakeholders in the region according to their traditional roles in the value chain.

	Production		**Distribution**		**Storage**		**Use**				
	Power Prod.	H2 prod.	Local	Reg/Nat	Small scale	Large scale	Sell to industry	Use inhouse	Energy	Support to grid	Transp. Fue
ABB											
Fertiberia Group											
Fortum											
Fu-Gen Energi											
H2 Green Steel											
Lhyfe											
Linde Gas											
Liquid Wind											
LKAB											
LTU											
Luleå Energi											
Nordion Energi											
RISE											
Skellefteå Kraft											
SSAB											
St1											
Statkraft Hydrogen Sweden											
Svenska Kraftnät											
SWECO											
Swerim											
Uniper											
Vattenfall											
W3 Energy											
Wpd Offshore Sweden AB											

Today, we see many activities and co-operations to support large industrial investments. For example, the power grid owners are striving to strengthen the power lines for the electricity demand, and companies like Nordion Energi are investigating to build hydrogen pipelines. For example, the Nordic Hydrogen Route (Nordic Hydrogen Route, 2022) is an initiative between Nordion Energi and Gasgrid Finland to create a cross-border hydrogen infrastructure between Sweden and Finland in the Bothnian Bay region by 2030. Moreover, Europe’s largest land-based wind farm is currently being established in Markbygden, in northern Sweden. There are also plans on producing further electricity from new wind farms, both on- and offshore. Component and energy system producers interact to support the investments. The public partners such as municipalities strive to prepare the society with everything needed to welcome thousands of more employees and their families to cover the huge new needs to run the new businesses. Universitates and institutes perform and offer research, development support and co-operations, as well as the consultancy firms build completing readiness to assist. The national authorities investigate the gaps in regulations and seek ways to support the extraordinary rushes the companies meet when regulations are not prepared for hydrogen in the energy and industry systems.

There are already funding for around 15 hydrogen refueling stations in northern Sweden to be built within four years, from the today only one existing station. The target is presented to run Inlandsbanan, the inland railway from North to South on hydrogen. There is at least one residential building, and one datacenter with hydrogen storage and use in fuel cells today. Luleå Hamn, ABB and Uniper are planning for hydrogen production and distribution in the harbour of Luleå.

Not least universities and institutes, such as Luleå University of Technology, RISE and Swerim, are investing in projects, research labs and research centres. New education tracks are given by municipalities and other stakeholders as well.

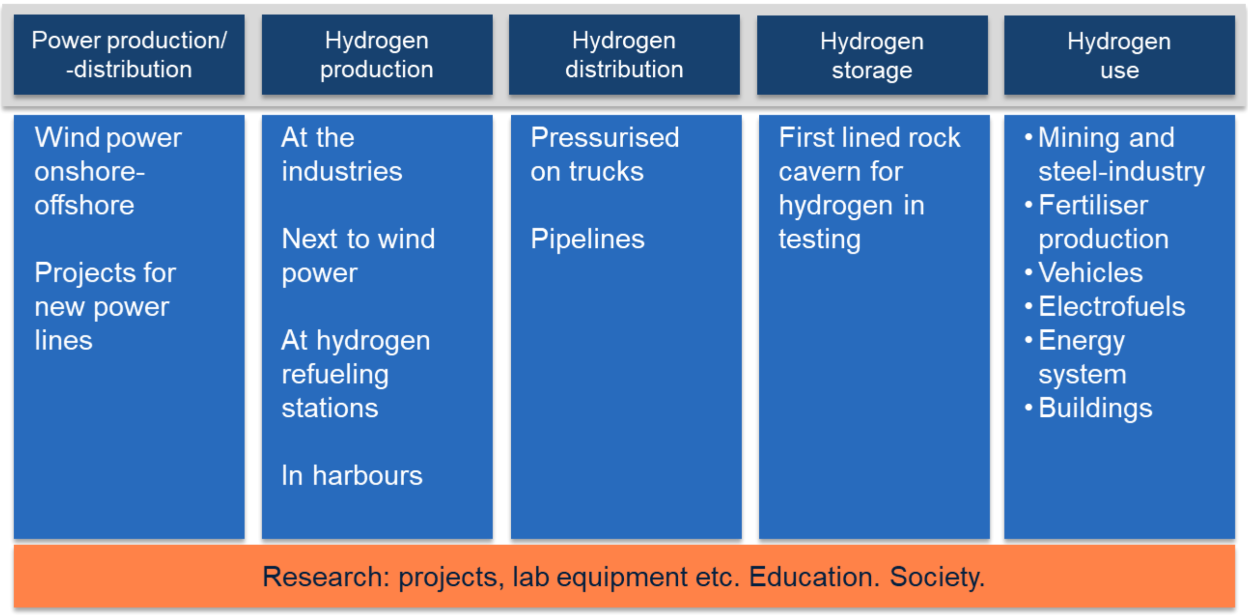

Figure 1. Overview of present investments along the hydrogen value chain in northern Sweden.

2.1.2 Current development in Norway

Hydrogen is considered a key contributor in Norway's ambition to become a low emission society by 2050. In general terms, the hydrogen development in Norway is largely shaped by the petroleum and maritime expertise in the country as well as methanol and ammonia as fuel and as feed stock to the industry.

Industry experience in oil and gas shows good landscape for Carbon Capture and Storage (CCS). Natural gas can be split into hydrogen and CO_2, the CO_2 is captured and then stored. As the greenhouse gasses are captured, this mitigates the environmental impacts even if a fossil source is used. Since Norway has more than 90% renewable energy in overall energy mix, there are good opportunities for producing fossil free hydrogen with electrolysers.

Main ambitions short term

Central for the Norwegian government policy towards 2030 is to support hydrogen technology development especially within maritime and heavy transport. Total estimated demand 2030 is 200 kton/year where 75% reflects demand for ammonia and methanol – i.e. alternate fuels.

The ambition is to build five hubs for production and distribution of hydrogen along the coastline. The possible export opportunities for Norway consists of hydrogen both produced via electrolysers and by reforming natural gas combined with CCS. Norway also sees opportunities to export offshore technology and maritime application experience. However, there are challenges with social acceptance, security in maritime transport is still discussed due to explosion at filling station 2019. There are also risks in being the first mover in terms of high investment costs.

Potential synergies with Sweden

There are potential synergies with Sweden and the rest of the Nordics. For example, due to Norway's high amount of renewable energy and a low electricity price, there are possibilities for Norway to produce hydrogen that can be transported to northern Sweden to meet their high demand in hydrogen.

Sweden is a first mover in using renewable hydrogen in the steel industry as well as the chemical industry, while Norway is a first mover in the maritime industry. By paring know-how in first mover industry, both Norway and Sweden can benefit. There are also possibilities to coordinate hydrogen hubs and available infrastructure with cross boarder demand.

In research and development, there are opportunities to synchronize public funding for collaboration projects between the Nordic countries.

2.1.3 Current development in Finland

So far, renewable hydrogen has not played a central role in Finnish industry. However, Finland currently possesses a clean and robust power system with cost-effective renewable electricity resources, comprehensive and solid energy infrastructure as well as a highly talented professional pool, which are all key requirements for success in the construction of a hydrogen economy (Hydrogen Cluster Finland, 2021). Hydrogen has until today been used for mainly oil refining, biofuel production and chemical industry. In general terms, the hydrogen development is largely driven by different Power-to-X solutions focusing on creating synthetic fuels.

Transition from fossil-based hydrogen to renewable hydrogen has started – a few larger projects have received financing. Fossil-free energy is available; established capacity of 3,200 MW corresponds to 10% of the power demand.

Main ambitions

One of the main drivers for Finland is the national goal of becoming carbon neutral by 2035, where hydrogen is to be a key part in especially the lowering of industries' emissions. Finland has an established capacity of 3 257 MW fossil free energy available, but increased wind power is still needed to secure sufficient renewable power to reach the set goals.

Since the focus for Finland is to reach their 2035 goal, this will be prioritized and when the goal is met, the focus will shift to exporting both products and knowledge, which allows for new product development and testing. New technology development of turbines, engines, methane decomposition and power-to-x solutions are areas that Finland will target.

Pure hydrogen export to southern Europe is not wanted from a political view, the focus should be on how to develop the ecosystem and knowledge in Finland as a first step. Since there are no separate hydrogen strategy in Finland. EU regulations are the main guidelines when it comes to developing the hydrogen sector.

Potential synergies with Sweden

Since both Finland and Sweden has experience within steel and forest industry, this provides opportunities for collaboration between companies in the two countries. There are ongoing collaboration and discussions around infrastructure and funding. For example, the BotH2nia network, which consists of universities, research organisations and companies in Sweden and Finland, aims to build a robust hydrogen industry around the Gulf of Bothnia and combine resources to pursue this common goal.

2.2 Outputs from interviews and discussions with consortium members in Sweden

The project consortium consisted of 27 members including RISE, LTU and Vinnova. The project members were organisations representing a wide span of company sizes and different parts of the hydrogen value chain. The sizes varied from SMEs with just a handful of employees to industry companies with many thousands of employees with activities from wind power production to chemicals and materials production.

The interviews were performed mainly in April-May 2022 and included further stakeholders than the project members.

In Appendix 2, a detailed summary of the output and expressed standpoints from the dialogues are sorted after topics. Further, conclusions, discussions and raised questions from the interviews are used as input to the work with regulations and prioritized future work.

2.2.1 General comments from the interviews

High power availability and low costs are enablers pointing out northern Sweden as an interesting area for development of an industrial ecosystem for production and use of hydrogen. The high environmental goals and sustainable energy mix in Sweden gives credibility to these efforts and has a positive impact on branding.

Large scale production, storage, transportation and use of hydrogen for energy purposes or in industrial applications is to some extent new applications for hydrogen in the Swedish industrial eco-system.

The transition of industrial sectors means that actors take on new roles in new value chains. Therefore, knowledge is missing in industry as well as in public sector and academia. And in all different areas not only technology but also economy, environment, law, safety, politics etc. To reach the full potential we must work more together. There is a need for more business-to-business collaboration and we need to be more creative in business development.

There are also factors that might slow down and limit the development. That is *for example*:

- Power supply might be a limiting factor. There might be a need to prioritize who should have access first and if so how should these priorities be made.
- Too long lead times for permits processes
- Limited availability of land in different projects

Safety issues connected to hydrogen development is pointed out as a top priority. This is an area that needs knowledge building and focus on all levels: technology development, legal and justice, rescue services, geopolitical issues etc. Best practices must be developed.

We must not solely put all efforts into hydrogen. We must also compare to other energy carriers.

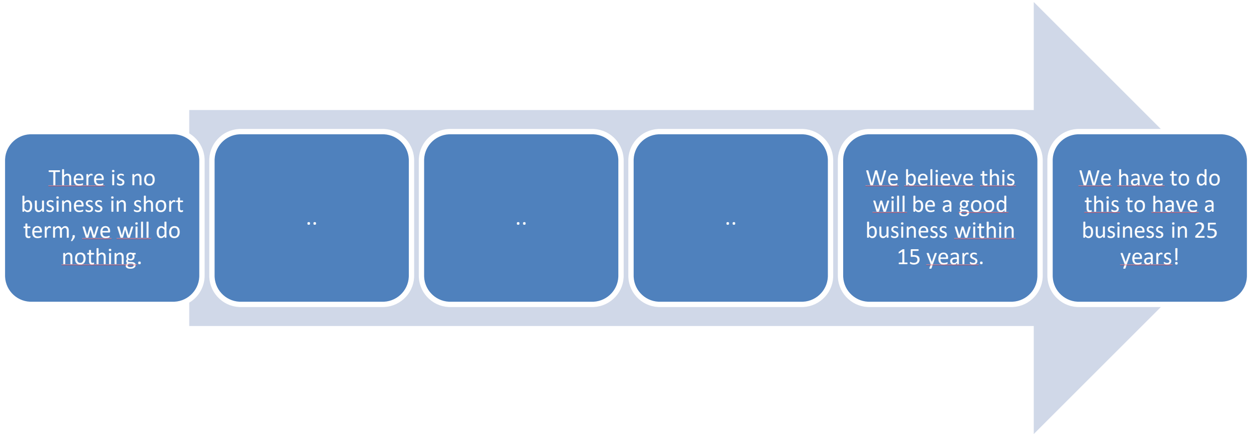

Figure 2. The variation of business readiness for hydrogen pipelines was shown diverse in the interviews with the project participants. Here illustrated by the view of hydrogen among the owners of a few stakeholders in the area.

2.2.2 On regulations and incentives from the interviews

According to the interviews with the project consortium, the below mentioned regulations and incentives are the most important for the development of a hydrogen energy system. In Chapter 3, current regulations and directives are described in more details.

An infrastructure for hydrogen storage and distribution can create a hydrogen market and thus be an opportunity for many stakeholders that wish to be players in this market. How this market should be regulated is of uttermost importance. It must be fair and available to all from SME to large industry corporations. Discussions on how this market should be regulated must start urgently. Uncertainty could delay important investment decisions.

Governmental activity is expected to be higher. The suggested national strategy by the Swedish Energy Agency, 26 November 2021 should be activated and evaluated. That would include facilitating permits, secure availability of land, policies etc.

Incentives to decrease investment risks is necessary to increase speed to market. This could be as support, or risk sharing, to “first to build”. The first plant/equipment is always much more expensive than the following. Alternatively, it could be some kind of green certificates etc.

There is a mismatch between Swedish and EU targets and stake holders fear that Swedish national interest is not being monitored enough. One example is the principle of additionality for renewable energy that is being discussed.

The municipalities have an important role in developing the hydrogen market. In part due to the municipal veto that often delay the permit process. To decrease this risk municipalities must be included in discussions at an early phase and there must be incentives for them to contribute. Municipalities could also take an important role when it comes to help realizing possibilities that might result from a hydrogen infrastructure. There could be important facilitators for future business and regional development.

Other standpoints in short

- There must be a geopolitical risk perspective on how a hydrogen networks best should be built.
- An assessment of the permit process is needed aiming at shortening time.
- TSO Grid and gas cooperation in needed
- There must be a common standard for hydrogen quality and sustainability calculations

3 Regulatory framework related to a hydrogen energy system

Over the next 30 years, major investments in hydrogen systems are planned in both Sweden and the EU. The technological development in the energy field is fast moving, which places high demands on the legal framework being up-to-date and applicable. In the EU, e.g. the existing gas market legislation is currently being revised to include hydrogen systems. The legislative “gas package” proposes a new regulatory framework for the market of transport, supply and storage of hydrogen.[1] The revised “gas package” is expected to be adopted in 2023 and enter into force in 2024, but there are voices that argue that it needs to (and can) go faster than that.[2]

In Sweden, the proposed national hydrogen strategy suggests that hydrogen pipelines likely will be used within hydrogen valleys (Swedish Energy Agency, 2021b) and other reports support the eventual development a national, connected to the European, hydrogen transmission network (Lara et al., 2021). There are currently no known on-going legislative efforts in Sweden to adopt a legal instrument, on a national level, specifically designated for hydrogen systems. Unlike many other European countries, Sweden has a relatively small network of natural gas pipelines. The introduction of this new infrastructure may lead to conflicts over land-use, given that there is no extensive tradition or knowledge of gas pipelines in Sweden. This is also why a clear regulatory framework is of great importance.

This chapter includes a presentation of existing and forthcoming regulatory framework in relation to the hydrogen value chain, from the origin of the electrical power and construction of its distribution grid, through the production, storage, pipeline distribution and usage of hydrogen. Furthermore, it includes regulations related the by-product oxygen from the hydrogen production through water electrolysis. At a high level, a scenario analysis of conditional aspects of existing, proposed, and missing laws and regulations for a hydrogen system is carried out. Both EU and national frameworks are included, in addition to regulations under development.

3.1 Methods and Scope

The work is based upon a GAP analysis: where are we today and where do we want to be? The target state and the identified obstacles are based upon literature and regulations surveys, interviews performed in the first parts of the project, as well as a workshop with the project partners in June 2022.

For the first part, the hydrogen transmission case, a scenario analysis to determine which regulations and permits will be applicable when constructing parts of a hydrogen system (pipeline, storage, and production facility), the legal dogmatic method will be applied. This involves an analysis of different legal sources, including legal text, preparatory works, and case law, in accordance with the theory of the sources of law. Regarding the text analysis, the study is qualitative. In addition to the legal dogmatic method, the environmental law method will be applied. The centrality of the environmental law method is to use the natural science to investigate the validity and consequences of legislation. The aim of environmental law is to protect nature and people from damage and other negative influences. An interdisciplinary approach is therefore considered necessary.

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[1] Proposal for a directive of the European Parliament and of the council on common rules for the internal markets in renewable and natural gases and in hydrogen COM (2021) 803 final and Proposal for a regulation of the European Parliament and of the council on the internal markets for renewable and natural gases and for hydrogen (recast) COM(2021) 804 final

[2] Hydrogen regulation under time pressure | Topic of the Month (eui.eu)

- **The hydrogen transmission case** is limited to an onshore hydrogen production through electrolysis and a pipeline to transport the hydrogen to the storage and to the users. In the scenario analysis, the regulations and permits applicable when constructing parts of a hypothetic hydrogen system case are analyzed with the main focus on the hydrogen pipeline.

For the following parts, starting with the power transmission case, a more general overview is provided for current regulations and processes for wind power plants and electrical grid expansion, and also for the regulatory framework for the use of hydrogen (and oxygen). Furthermore, selected legislations at EU and national level, both existing and under development, are described.

- **The power transmission case** is limited to large wind power plants as a source for electricity, onshore or offshore, and to expansion of the grid and the application and administrative and practical process related to that.

The mandate underlying this prestudy is clearly limited in scope as well as in time, which has meant that there has been no opportunity for a deeper analysis of the proposed Swedish and EU legislations. This is thus only briefly touched upon. For the same reason, all property law issues have been excluded.

3.2 Introduction to Swedish key documents

Elektrifieringsstrategin (Infrastrukturdepartementet, 2022)

The Swedish national strategy for electrification provided in 2022 the government's view on and suggestions to improve the rate of electrification as a mean to reach the climate goals. One of the main goals is that sufficient electrical capacity and power need to be provided where and when it is needed. This will require more efficient use of the current grid and faster expansion of the grid. A clear energy system perspective should guide the electrification. Hence, also the role of hydrogen in the energy system is acknowledged and, hence, it is suggested that a national strategy for hydrogen, based on the current proposal,(Swedish Energy Agency, 2021b) should be developed and that the possibilities to introduce tariffs for hydrogen pipelines are analyzed.

Vätgasstrategin (Swedish Energy Agency, 2021b)

The proposal for a Swedish Hydrogen Strategy has proposed that by 2030 it should be possible to install 5 GW of electrolysis capacity and by 2045 a total of 15 GW. More generally, it is described that the hydrogen system, and how it interacts with existing energy systems, need to be analyzed. Also, a set of measures in several areas are proposed, e.g.:

- Regulations should enable concession for hydrogen pipelines.
- Investigation of the need for additional policy instruments that reduce the cost gap between fossil-free and fossil hydrogen.
- In the absence of natural geological conditions for large-scale storage, storage of hydrogen in Sweden can be expected to take place in conventional hydrogen storage tanks or lined rock cavern can offer more large-scale storage, but only after testing and evaluating the technology.
- That the necessary regulation is put in place is a prerequisite, partly for the use of hydrogen to contribute to climate neutrality in a sustainable way, and partly to create clear rules of the game and thereby conditions for further investments.
- Regulatory framework for the production, distribution and storage of hydrogen should be investigated and adapted and updated with security in focus.
- Permit processes for the hydrogen system need to be streamlined and lead times shortened.

Miljöbalk (1998:808)

The Swedish Environmental Code (1998:808) entered into force January 1st 1999 and the goal was to bring together and systematize the legislation within the field of environmental law. The purpose and aim of the Environmental Code are codified in the opening section:

Ch. 1 s. 1 The purpose of this Code is to promote sustainable development which will assure a healthy and sound environment for present and future generations. Such development will be based on the recognition of the fact that nature is worthy of protection and that our right to modify and exploit nature carries with it a responsibility for wise management of natural resources.

The environmental Code ***shall be applied*** *in such a way as to ensure that:*

1. *human health and the environment are protected against damage and detriment, whether caused by pollutants or other impacts;*
2. *valuable natural and cultural environments are protected and preserved;*
3. *biological diversity is preserved;*
4. *the use of land, water and the physical environment in general is such as to secure a long term good management in ecological, social, cultural and economic terms; and*
5. *reuse and recycling are encouraged with a view to establishing and maintaining natural cycles.*

By reading the above, it is clear that the Environmental Code has a vital role in the fight against climate change, pollution, loss of biodiversity and so forth. The code contains, among much else, provisions on management of land and water, protection of areas and permits for hazardous activities. For the individual operator it is important to know and understand the purpose of the code to better understand why some actions are required from courts and authorities.

3.3 The hydrogen transmission case

The hydrogen transmission case presented here is based on a hypothetical hydrogen system with separate operators for production, storage, and distribution. The hydrogen production facility needs electricity and water and will therefore be situated near a natural water source and connected to wind power, either through grid or direct connection. The technique used for the hydrogen storage is a lined rock cavern (LRC), which means that it is dependent upon certain geological conditions and demands massive spaces (Papadias & Ahluwalia, 2021). The hydrogen pipeline will run through hard-rock terrain, a Natura 2000 site, next to a nature reserve and over some water sources. The length of the pipeline is 60 km. The purpose of the case is to simulate an actual situation to highlight some of the different considerations an operator needs to make when planning to construct a part of a hydrogen system. The case is separated into parts: distribution, production, and storage of hydrogen. This case is not intended to be an in-depth legal analysis, but rather to give an overview of what laws and regulations that operators must comply with, particularly the Swedish Environmental Code (1998:808), and at the same time note any lack of legal regulation in the area.

3.3.1 The hydrogen pipeline

In the first part of the hydrogen transmission case, the focus is on the legal prerequisites and permits for constructing a hydrogen pipeline with a length of 60 kilometers. The hydrogen pipeline starts at the hydrogen production facility and leads to an existing industry. The pipeline will be placed underground. In this chapter, concession, permit for environmentally hazardous activities, and permit for water operations will be examined. In addition to these permits, the operator must also apply for management right[1] to be able to construct a hydrogen pipeline on land belonging to another legal or natural person.

[1] Ledningsrätt.

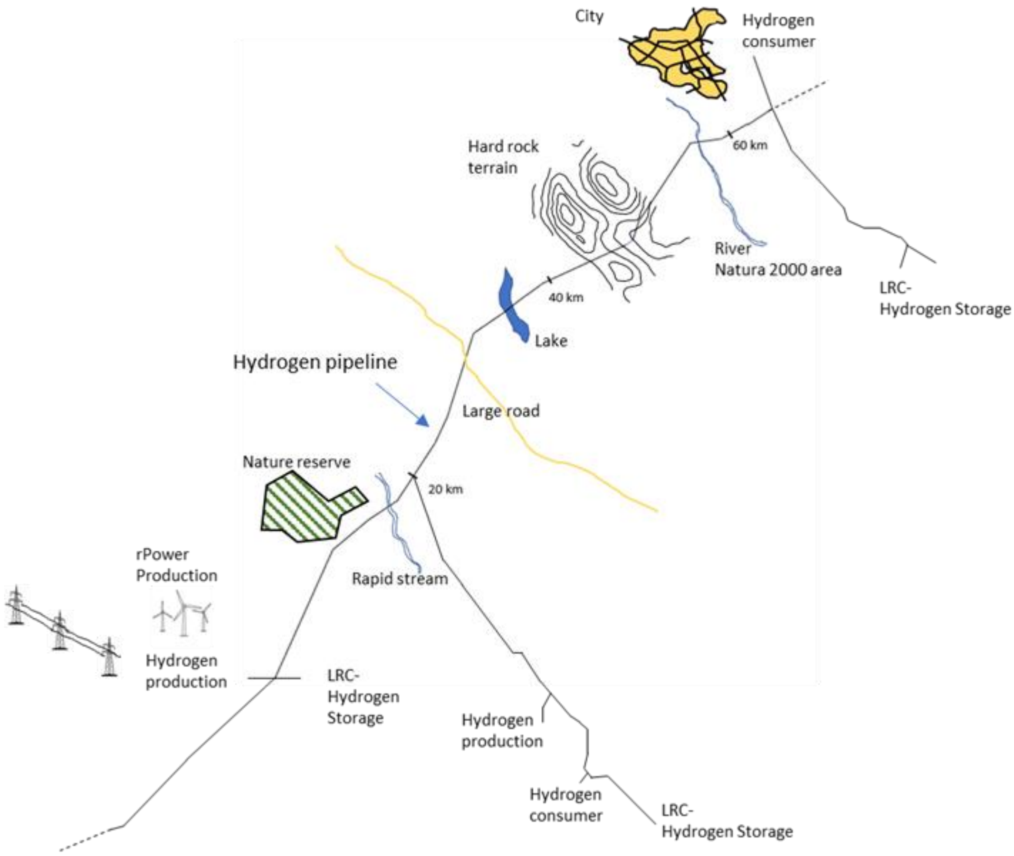

Figure 3. Schematic of the hypothetical hydrogen energy system analyzed.

Concession

Concession is in most cases required for the construction and operation of gas pipelines. Concession is a form of permit that gives the holder certain rights and responsibilities within the scope of the concession and as a result also a stronger stance against competing interests. In Sweden, there is currently no legislation specifically developed for the concession of hydrogen pipelines. In the coming years, legislation regarding hydrogen markets including hydrogen pipelines and hydrogen storage is expected to come from the EU (which is further described towards the end of this chapter).[1] This will probably require Sweden to regulate some parts of the hydrogen market and which in turn could lead to a concession requirement for hydrogen pipelines. Until then, two laws are of interest: the Act (1978:160) on certain pipelines (hereinafter the ACP) and the Natural Gas Act (2005:403) (hereinafter the NGA). Currently it is unclear whether it is possible to grant concession for a hydrogen pipeline under the ACP or the NGA. It can be argued that none of these regulations are applicable, which means that a concession will not be required.

Concession according to the Act on Certain Pipelines

Section 1 of the ACP states that pipelines for the transport of, *inter alia*, gas suitable for use as fuel may not be constructed or used without a special permit, concession. In the term pipeline is also included the necessary accessories and devices for the operation.[2] This may imply a concession obligation for hydrogen pipelines depending on the interpretation of the word fuel. The ACP has however rarely been used in caselaw and the preparatory works lacks definition or explanation of the meaning of the word fuel. Hence, it is not certain that the ACP will be considered applicable on

[1] COM (2021) 803, Förslag till Europaparlamentets och rådets direktiv om gemensamma regler på de inre marknaderna för förnybar gas, naturgas och vätgas och COM (2021) 804, Förslag till Europaparlamentets och rådets förordning om de inre marknaderna för förnybar gas, naturgas och vätgas.

[2] S. 2 of the Act on Certain Pipelines

hydrogen pipelines. On the other hand, the lack of definition or explanation can be reason to argue for a wide interpretation of the word fuel therefore allowing hydrogen to fall within the scope of the law. The other predicament concerns the actual use of hydrogen; if the hydrogen is not used as fuel, then the ACP is not applicable.

The issue of concession is examined by the government and the concession application is submitted to the Swedish Energy Markets Inspectorate. As stated above, the ACP is a relatively old legal act that has rarely been used which can imply that the authorities and the government lacks routines for how to handle a concession application within the ACP, which in turn could lead to prolonged proceedings, on the other hand, the application process is relatively similar to applying for concession under the NGA. The Government's concession decision is binding in the event of a review under the Environmental Code, which effects the permit process for environmentally hazardous activities and water operations (see next section).

If the operator decides to seek concession according to the ACP, the rules regarding the application are found in section 1 of the (1978:164) regulation on certain pipelines. The first step is to ensure that the pipeline is necessary from a public perspective and complies with outlined energy policies.[1] Hydrogen is considered an important part of the reduction of carbon emission from large industries because of its function to store and provide fossil free energy. A hydrogen pipeline will be essential to store energy and to carry hydrogen from production sites to industries. Today hydrogen can also be transported via trucks, but pipelines are a more efficient way to transport substantial amounts of hydrogen over longer distances. In the Swedish strategy of electrification, hydrogen is pointed out as a key factor (Infrastrukturdepartementet, 2022). Hence, a hydrogen pipeline should comply with outlined energy policies.

Furthermore, a concession must not contravene current area regulations and detailed development plans, which can hinder the construction process as such plans can take a long time to revise, which is why a careful investigation is needed when considering where the pipeline should run.[2] For hydrogen pipelines to be used it must be able to reach designated industries, hydrogen storages and hydrogen production facilities why the different operators within the hydrogen system should find ways to collaborate in early stages.

The concession must also comply with chapters 2-4, chapter 5 sections 3-5, 18 and chapter 6 of the EC. This includes provisions on land use, environmental considerations, requirements due to environmental quality standards, as well as the environmental assessment and environmental impact statement that must be added to the application for a permit.

A permit application shall contain a description of the proposed activity and how the operator plans to comply with the general consideration rules[3] in chapter 2 of the EC.[4] The following requirements are imposed on the operator on the basis of the general rules of consideration:

- sufficient **knowledge** about the environmental impacts of the activity
- undertaking of preventive and **protective measures** and precautions
- **substitution** of dangerous chemicals
- management of natural resources and energy, including the reduction of the amount of waste
- investigate suitable locations and select the one that causes the least damage and inconvenience to the environment
- measures to remedy existing damage and inconveniences.[1]

[1] [1] S. 4 of the Act on Certain Pipelines.
[2] S. 4 of the Act on Certain Pipelines.
[3] Hänsynsregler.
[4] The burden of proof, i.e., the responsibility to show that the activity complies with the rules thus lies on the operator (Ch. 2, s. 1).

While the rules do not per se refer to the protection of sensitive nature and biodiversity, the requirement for protective measures and location together with the so called “stop rule”[2] mean that both the sensitivity of the area and any nature conservation restrictions must be considered.

In relation to the use of land for the installation, the activity must also be compatible with the EC’s resource management provisions[3], including areas of national interests[4]. The premise is that land and water areas should be used for the purpose for which the area is most suitable, considering the nature, location and uses entail from a general point of view good management.[5] The first category of management rules is found in chapter 3 of the EC which specifies which areas, including areas of national interests, that must be considered when deciding land-use issues. As an example, large areas of land and water that have not previously been affected by exploitation or the like *should, as far as possible, be protected*[6] and the same applies to land and water areas that are sensitive from an ecological point of view, as well as land and water areas that are important for natural values, cultural value or outdoor life.[7] If the area is of national interest, *it shall be protected* against such measures that could significantly harm nature or the cultural environment.[8] Areas may also be of national interest for industrial production, mineral extraction and energy production. Swedish national authorities are responsible for designating areas of national interests. It is a possibility that areas that are particularly suitable for hydrogen systems will become a national interest and hence have stronger stance in relation to other competing interests. While the authorities’ designations are not legally binding, they have a strong normative effect in the planning and permitting process. If an area is suitable for two incompatible interests, the law states that preference shall be given to the purpose that most appropriately promotes a long-term management of land, water, and the physical environment in general.[9] The second category of management rules is found in chapter 4 of the EC and concerns certain geographical areas that are considered national interests. These areas are of national interest for their natural, cultural or recreational values.[10]

Natura 2000 sites are such national interests, which means that *they must be protected*.[11] In this case we have decided that the pipeline will run through a Natura 2000 site to demonstrate how this affects the process. A special permit is required for activities on a Natura 2000 site if it is likely to affect the environment within the area in a significant way.[12] For each Natura 2000 site there is a unique conservation plan that must be studied to determine whether the specific operation will affect the protected interests/values. An underground pipeline entails digging up soil in the area and a need for excavators to enter the area which could have a significant impact. If the operator is unsure whether the operation will affect the area in a significant way, it is possible to contact and consult with the relevant county administrative board. As a main rule, activities that may significantly impact a Natura 2000 area require a permit. A permit may in turn not be granted if the activity itself or together with others can be assumed to damage or disturb the habitat or the protected species in question in a way that may impede the conservation of the species. The derogation regime, i.e., to be granted permit even though the operation may cause considerable damage, requires that all the following requirements are met:

- the activity must be carried out for imperative reasons having an essential public interest,

[1] Ch. 2. s. 2-6 of the Environmental Code.
[2] Ch. 2 s. 9-10 of the Environmental Code.
[3] Hushållningsbestämmelser.
[4] Riksintressen.
[5] Ch. 3 s. 1 of the Environmental Code.
[6] Ch. 3 s. 2 of the Environmental Code.
[7] Ch. 3 s. 3 of the Environmental Code.
[8] Ch. 3 s. 6 of the Environmental Code.
[9] Ch. 3 s. 10 of the Environmental Code and also MÖD 2010:38 Glötesvålen.
[10] Ch. 4 s. 2-6 of the Environmental Code.
[11] Ch. 7 s. 28a of the Environmental Code.
[12] Ch. 7 s. 28a of the Environmental Code.

- there is a lack of alternative solutions as well,
- measures are taken as necessary to compensate for lost environmental values so that the purpose of the protected area can nevertheless be met.

If the activity is deemed to affect a Natura 2000 site, a permit may only be granted with the Government's permission.[1]

The concession application needs also to take into account environmental quality standards (hereinafter EQS) which are legal standards that specify levels of pollution or disturbance that must not be exceeded, or the highest or lowest occurrence of levels of organisms in water.[2] If an activity entail that an EQS will not be followed, the adjustment of the requirements following the application of the general consideration rules, that can otherwise be made on the basis of Ch. 2, s.7, is not applicable. Another effect of EQS is that an application for permit may be rejected if the account for the EQS in the environmental impact statement is insufficient.[3]

The operator is bound to create an environmental impact statement[4] (hereinafter EIS) according to chapter 6 of the EC. The EIS precedes the decision to grant a concession and aims to improve the basis for the decision through the development of a special document: environmental impact assessment[5] (hereinafter EIA). The function of the EIS is to raise awareness among the public, the decision-maker and the operator. The EC summarizes the purpose of EIS as integrating environmental aspects into planning and decision-making so that sustainable development can be achieved.[6] Among the environmental aspects to be considered, the environmental impacts are central. In principle, any effect on the external environment (including biodiversity, climate, cultural environment, energy conservation, materials and energy), population and human health – directly or indirectly, positive or negative, temporary or permanent, cumulative or not, that occurs in the short, medium or long term constitute an environmental effect.[7] The EIS shall also include assessments of risks, existing environmental conditions, relevant environmental objectives and standards, measures to prevent, prevent and counteract adverse environmental effects and the assessment of possible alternatives.[8] EIS also include consultation procedures.

A specific EIS is required for activities that are likely to have significant environmental impacts or affect a Natura 2000 site.[9] Some activities are always expected to require specific EIS such as certain environmentally hazardous activities, certain water operations and infrastructure facilities (pipeline *inter alia*).[10] The operator is responsible for the content of the EIA, such as location and design, environmental conditions, identification and assessment of environmental effects caused by the activity, measures to prevent and counteract the remediation of adverse environmental effects and information on alternative solutions. An in-depth analysis is therefore required by the operator to establish what effects on the environment and human health the pipeline will have, this includes risk of a breach in any way, how the construction process will affect the environment, materials in the pipeline and more. This part of the concession is of major importance as the concession decision is binding upon review by the EC. Hydrogen pipelines is a new type of operation which entail that a lot will be demanded from the operator regarding the environmental considerations.

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[1] Ch. 7 s. 29 of the Environmental Code.
[2] See chapter five of the Environmental Code.
[3] See MÖD 2012:19.
[4] Miljöbedömning.
[5] Miljökonsekvensbeskrivning.
[6] Ch. 6 s. 1 of the Environmental Code.
[7] Ch. 6 s. 1 of the Environmental Code.
[8] Ch. 6 s. 11 and 35 the Environmental Code.
[9] Ch. 6 s. 24-26 of the Environmental Code.
[10] S. 6 p. 5 of the Environmental Assessment Regulation (2017:966).

Concession according to the Natural Gas Act

As noted above, a gas pipeline can be granted concession under the ACP. However, natural gas pipelines are exempted from the ACP[1] and is instead regulated in the NGA. The NGA contains provisions regarding natural gas pipelines and storage facilities[2] and lacks directly applicable provisions on the construction of hydrogen pipelines and hydrogen storage. The NGA states that natural gas also means biogas, gas from biomass and other gases to the extent that it is technically possible to use these gases in a natural gas system.[3] The wording in this section means that if hydrogen is used in a natural gas pipeline it would be considered, in legal terms, a natural gas. Hydrogen can up to a certain extent, e.g. up to 5%, be blended into the natural gas grid hence it is technically possible to transport some hydrogen through the natural gas system. Also, existing natural gas pipelines may be repurposed into hydrogen pipelines.(Wang et al., 2020) However, it is uncertain whether such a repurposed pipeline would fall within the scope of the Natural Gas Act, since it is not considered technically possible to use only hydrogen in a natural gas pipeline without major alterations to the construction of the pipeline. If these alterations are made – is it still a natural gas pipeline or is it then a hydrogen pipeline which would fall outside the scope of the NGA?

A natural gas pipeline requires concession[4] except for natural gas pipelines located after metering and regulating stations.[5] A basic condition for concession is that the installation is considered suitable from a general point of view. An assessment must therefore be made to demonstrate that there is an actual need for the pipeline or installation in question in light of existing pipeline systems and how well it complies with adopted energy policy guidelines.[6] Furthermore, a concession must not contravene current area regulations and detailed development plans, which in practice means that the municipality can control where pipelines may or may not be built.[7] Just as under the ACP, the concession assessments according to the NGA must comply with chapters 2-4, chapter 5 sections 3-5, 18 and chapter 6 of the EC (see above in chapter 1.2).[8]

The NGA does not only provide rules for the construction of infrastructure but also for the natural gas market. If hydrogen is to be used within a natural gas system according to the NGA, the market rules will also apply, and in a market sense hydrogen will be labelled as natural gas. A legal entity engaged in the transmission of natural gas is not allowed to conduct trade with or production of natural gas. Corresponding restrictions apply to a member of the Board of Directors, the Managing Director or the signatory in the case of companies holding concessions and companies trading in or producing natural gas.[9] A company engaged in the transmission of natural gas, and which is part of the same group as a company engaged in the production or trading of natural gas is required to establish a monitoring plan and ensure compliance with the plan.[10] Similar rules apply to a legal entity holding a natural gas storage facility. The company holding a storage facility is not allowed to engage in the production of or trade in natural gas. When a company is part of such a corporate group, its organisation and decision-making procedure must be separate from the companies engaged in the production of, or trading in, natural gas.[11] In general, the NGA contains more extensive regulation for operators within the natural gas system regarding ownership, reporting and monitoring than the ACP, this partly to counteract market abuse, monopolistic activities, and distorted competition within the EU gas market.

[1] See s. 1 of the Act on Certain Pipelines.
[2] Ch. 1 s. 1 of the Natural Gas Act.
[3] Ch. 1 s. 2 of the Natural Gas Act.
[4] Ch. 2 s. 2 of the Natural Gas Act.
[5] Ch. 2 s. 1 of the Natural Gas Act.
[6] Ch. 2 s. 5 of the Natural Gas Act.
[7] Ch. 2 s. 6 of the Natural Gas Act.
[8] Ch. 2 s. 7 of the Natural Gas Act.
[9] Ch. 3 s. 2 and 2a-f. of the Natural Gas Act.
[10] Ch. 3 s. 9 of the Natural Gas Act.
[11] Ch. 4 s. 1 of the Natural Gas Act.

The NGA also contains rules regarding the revenues of natural gas, from the transmission and storage of natural gas a revenue framework is to be calculated in such a way as to cover the reasonable costs of carrying out the activities covered by the revenue framework and provide a reasonable return on the capital required to carry out the business.[1] The supervisory authority announces decisions on the revenue framework that apply to a certain supervisory period, normally four years.

In addition, the NGA holds provisions on system balance responsibility[2] and balancing responsibility[3] in the natural gas market. The national natural gas system, the so-called West Swedish natural gas system (since it mainly runs along the Swedish west coast), is the responsibility of a specially appointed system balance manager, who is thus responsible for maintaining the balance in the short term between the input and withdrawal of natural gas.[4] The owner of a natural gas pipeline used for the transmission of natural gas that is not connected with the West Swedish natural gas system, is responsible for maintaining the balance in the short term between the input and withdrawal of natural gas.[5] The Government or, upon consent by the Government, the regulatory authority may provide regulations regarding obligation for the legal entity in charge of the transmission of natural gas to provide the system balance operator with the information necessary for the exercise of system balance responsibility.[6]

As mentioned before the hydrogen used in a natural gas system will become a natural gas in legal terms and that may lead to unwanted effects in regard to subsides, taxation and so forth as these rules were not created for hydrogen systems especially not green hydrogen. A further analysis is needed to understand what effects this would have.

No concession
If neither the ACP nor the NGA would be considered applicable, a concession will not be needed. The pipeline will however still require a management right and sections 6-10 of the Utility Easements Act (1973:1144)[7] (hereinafter the UEA) will become applicable. A general needs and suitability assessment will thus precede the granting of a management right.[8] The suitability assessment is based on the Swedish mapping, cadastral and land registration[9] authority examining if the purpose of the management ordinance should be fulfilled in any other way than what the applicant has requested. In the balancing of interests that arises both when choosing between different alternatives and when only one solution is available, the benefits of the grant must be weighed against the inconveniences from both a public and private point of view. If the inconvenience outweighs the benefits, no management right can be granted. The examination thus includes an assessment of whether the grant is appropriate and necessary. Since the UEA is a compulsory legislation, the interests of the owner of the utility line must be balanced against the property owner's interests. The provisions of the UEA are primarily aimed at protecting opposing individual interests but they also protect public interests such as nature conservation views.[10] A great advantage of obtaining a concession is that it gives the operator a stronger stance in relation to the regulations in the EC as the Government’s concession decision is binding in the event of a review under the Environmental Code. This is not the case if the operator only has a management right.

[1] Ch. 6 s 10 of the Natural Gas Act.
[2] Systembalansansvar.
[3] Balansansvar.
[4] Ch. 7 s. 1 of the Natural Gas Act.
[5] Ch. 7 s. 2 of the Natural Gas Act.
[6] C. 7 s. 3 of the Natural Gas Act.
[7] Ledningsrättslagen (1973:1144)
[8] S. 6 of the Utility Easements Act.
[9] Lantmäteriet.
[10] S. 8-10 of the Utility Easement Act.

Permit for environmentally hazardous activities

Environmentally hazardous activities are defined as any use of land, building or facility that causes or may result in emissions into soil or water, pollution of soil, air or water or inconvenience to the surroundings of any other kind.[1] Most activities that entail or risk to imply negative environmental or human health impacts are thus defined as environmentally hazardous under the EC. Not all such activities however require a permit – in the main, environmentally hazardous activities that require a permit are listed in the Environmental Assessment Regulation. Hence the next question is whether a hydrogen pipeline is constitutes an environmentally hazardous activity and whether it is in that case subject to a permit requirement under chapter 9 of the EC. A hydrogen pipeline involves the handling of hydrogen gas, which itself is a flammable gas. There are no provisions in the Environmental Assessment Regulation that specifically targets a hydrogen pipeline, and it can therefore be concluded that no permit requirement (yet) has been established for the activity. If a pipeline is not subject to a permit obligation arising from regulations issued pursuant to ch. 9 s. 6 of the EC, it is still possible for the supervisory authority to decide that the operator must apply for a permit anyway, for example if the activity entails a risk of significant pollution or other significant harm to human health or the environment.[2] A hydrogen pipeline containing hydrogen may entail such a risk, and a permit may therefore be required.

If the pipeline has been granted concession, a prohibition may not be issued under the Environmental Code against the withdrawal or use of a pipeline.[3] This does not concern such restrictions that follow from Natura 2000 sites, National Parks or other protected areas. This section in the ACP puts certain limitations on the scope of the assessment since a rejection of permit is highly unlikely. The operator will already have made an extensive EIS and in showed in the application how the rules of the EC are followed.

Permit for water operations

Water operations are defined as activities that affect water sources (e.g. rivers, streams, lakes, etc.) in different ways.[4] Water operations require a notification or permit to be conducted, and unlike permits for environmentally hazardous activities where the permit obligation cannot be inferred from the provision in ch. 9 s. 6 of the EC but is regulated in regulations, the permit obligation for water operations is stated directly in the EC.[5] Laying down a pipeline in a water area is a measure that requires notification or permit of water activities before the construction of such a pipeline has begun.[6] For the case presented here, the area of the water operation (passing streams, rivers and a larger lake) is larger than 3000 sqm, which means a permit is required. The first step of a water operation is to obtain legal control[7] over the water. This is a procedural prerequisite, which means that an application for a permit will be rejected and not examined on the merits if the control is lacking.

The operator also needs to comply with the rules of chapters 2-5 of the EC, if the operator would have been granted a concession under the ACP or the NGA, then these considerations would already have been made. The scope of the assessment will then be limited to decide if the stop rule in ch. 2 s. 9 would impede the operation.[8] However, the court still must prescribe conditions for the activity based on the requirements for precautionary measures.

In addition to the general consideration rules, there are also specific requirements for water operations in chapter 11 of the EC on consideration of competing water operations and fisheries. Water operations shall be carried out in such a way that they do not impede other future activities that may

[1] Ch. 9 s. 1 of the Environmental Code.
[2] Ch. 9 s. 6a of the Environmental Code.
[3] S. 23 of the Act on Certain pipelines.
[4] Ch. 11 s. 3 of the Environmental Code.
[5] Ch. 11 s. 9 of the Environmental Code.
[6] S. 19 p. 8 of the Regulation on Water Operations (1998:1388).
[7] Rådighet.
[8] Ch. 11 s. 23 of the Environmental Code.

need the same water supply. The competing business is to be assumed to be realised in a "not too distant future" which, according to the proposition, is about 10 years.[1] The second requirement is an obligation for the operator to take measures to protect or promote fishing in the area and the surrounding area of the water operation.[2] This could mean building playgrounds for fish and other water living animals or to plant new fish in the area.

The permit process for environmentally hazardous activities and water operations are are similar and that is why the legislator has made it possible to assess both permits in the same process.[3]

The pipeline will also activate the coastal protection rules. The coastal area is defined as the area 100 m out in the water and 100 m on land. The aim of the coastal protection is to protect and preserve natural water ways against intrusion, why the main rule is that all such activities in the coastal area are prohibited. There are however several exemptions to the rule, for example if the activity has already obtained a water operation permit.

Act on Flammable and Explosive Goods

The Flammable and Explosive Goods Act (2010:1011) applies to the handling, transfer, import and export of flammable and explosive goods as well as preventive and subsequent measures.[4] The purpose of the law is to counteract accidents and injuries to people and the environment. With flammable goods is intended flammable gases, flammable liquids and fire-reactive goods.[5] Explosive goods are explosives and mixtures, explosive articles and other substances, mixtures and articles the purpose of which is to produce an active by an explosive or pyrotechnic effect.[6] The act contains various requirements for the handling of the goods, including duty of care, investigation requirements, competence requirements, manager requirements, etc.[7]

Furthermore, a permit is required for the person handling, transferring, importing, or exporting explosives or anyone who handles flammable goods professionally or in large quantities. If the operation concerns a pipeline with concession according to the ACP or the NGA, it is exempted from the permit requirement. The operation must however still meet the requirements for permitted activities set out in the Flammable and Explosive Goods Act.[8]

Act on Measures to Prevent and Limit the Consequences of Serious Chemical Accidents

The purpose of the Act on Measures to Prevent and Limit the Consequences of Serious Chemical Accidents (1999:381) (hereinafter The Seveso act) is, as the name suggests, to prevent and limit consequences of chemical accidents. The Seveso Act applies to activities where certain hazardous substances are present in an activity.[9]

Operators are obliged to take preventive and damage reductive measures that vary depending on the quantities of hazardous chemical substances handled in the process. In addition, the responsible party is obliged to consider the rules in chapter 2 of the EC.[10] The responsible party must notify the county administrative board of the activities unless the operation is subject to a permit requirement in accordance with the Environmental Code and the Government has issued regulations restricting the notification obligation.[11]

[1] Prop. 1997/98:45, del 1, s. 130.
[2] Ch. 11 s. 8 of the Environmental Code.
[3] C. 21 s. 3 of the Environmental Code.
[4] S. 1 of the Flammable and Explosive Goods Act.
[5] S. 3 of the Flammable and Explosive Goods Act.
[6] S. 4 of the Flammable and Explosive Goods Act.
[7] S. 6-16 of the Flammable and Explosive Goods Act.
[8] S. 16 of the Flammable and Explosive Goods Act.
[9] S. 3 of the Act on Measures to Prevent and Limit the Consequences of Serious Chemical Accidents
[10] S. 6 3 of the Act on Measures to Prevent and Limit the Consequences of Serious Chemical Accidents
[11] S. 7 3 of the Act on Measures to Prevent and Limit the Consequences of Serious Chemical Accidents and s. 5 of the regulation on Measures to Prevent and Limit the Consequences of Serious Chemical Accidents

Summary for hydrogen pipeline

It is not clear if a hydrogen pipeline in Sweden needs, or could obtain, a concession; and if so if it can be granted according to the ACP or the NGA by the government. In the concession process, the transmission pipeline operator must produce a specific EIS and consider the rules of considerations, the resources management provisions, and the environmental quality standards.[1] The operator will also need to procure a management right for the land- and water areas below which the pipeline will lay. It is the Swedish mapping, cadastral and land registration authority that examine and decide on the management right. Furthermore, it is likely that the pipeline will need a permit both for environmentally hazardous activities and water operations. These permits are assessed (in tandem) by the land and environmental court. A permit in accordance with the flammable and explosive goods act is not required if the operator has been granted concession, although the substantive rules of the act still must be observed.[2] The activity must also comply with the rules of the Seveso legislation. In sum, a lot is unclear when it comes to a legal framework for hydrogen pipelines - for several important aspects sufficient regulation is lacking. If the EU adopts a new gas legislation (see later in this chapter), this will most likely result in a need to revisit the Swedish gas market rules.

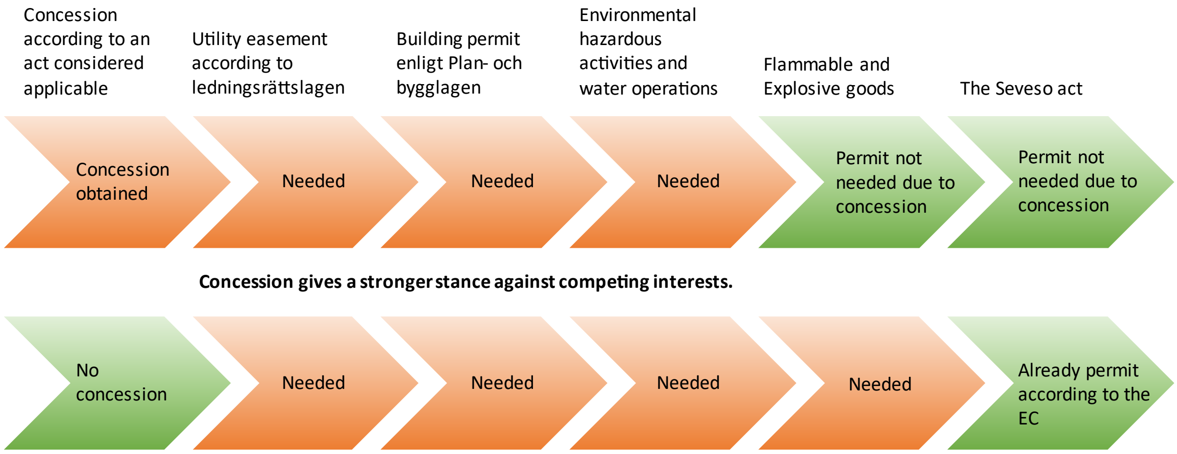

Figure 4. Schematic description of the permit processes needed (red) or not (green), for a hydrogen pipeline with, above, and without, below, concession, respectively.

3.3.2 The hydrogen storage

Concession

There are no concession rules for gas storage in the ACP. There is, however, a concession requirement for natural gas storage in the NGA. While the law is thus not directly applicable to a hydrogen storage facility it should be applicable *if* it is technically possible to store the hydrogen in a natural gas storage. As mentioned earlier it is possible to blend a small amount of hydrogen into the natural gas system but it would then be considered a natural gas. It is unclear if it is possible to repurpose natural gas storages to hold only hydrogen. A concession requirement does not exist for a storage used only for hydrogen.

The Electricity Act

Energy storage is defined and regulated in the new electricity market directive.[3] Sweden has implemented the rules pursuant to the new directive and they entered into force on the first of July

[1] See chapters 2-6 of the Enviromental Code.
[2] S. 16 of the Flammable and Explosive Goods Act
[3] Directive (EU) 2019/944 of the European parliament and of the council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU.

2022.[1] The purpose of energy storage is postponing of the final use of electricity to later point in time than when it was generated, by the conversion of electrical energy into a form of energy which can be stored, and the storing of such energy, as well as the subsequent reconversion of it into electrical energy or use as another energy carrier.[2] An energy storage facility is defined as, in the electricity system, a facility where energy storage occurs.[3] In the government bill, the definition of an energy storage facility is essentially the same as in the directive. However, as a clarification, it is stated that the installation must be used for energy storage.[4] In the commentary to the amendments of the electricity act it is concluded that hydrogen storage is such a facility that can be used for energy storage.[5] Hence, the electricity act can regulate the market for hydrogen storage facilities, if the hydrogen storage is considered to be a part of the electricity system. In such a case the hydrogen storage cannot be owned nor operated by electricity grid operators, The implications this will have for the hydrogen system and market are unclear and needs to be investigated further.

Environmentally hazardous activities

Whether a hydrogen storage facility needs a permit under chapter 9 of the EC is regulated in the Environmental Assessment Regulation. According to Ch. 20. S. 2 of the Environmental Review Ordinance permit obligation C applies for the installation of a facility containing flammable gases if the facility has the capacity for storage of more than 5000 tons at the same time or handling of more than 50,000 tons per calendar year. It is not certain what the maximum storage capacity is for hydrogen storage facilities but probably below 5000 tons at the same time, at least for each individual cavern.(Papadias & Ahluwalia, 2021) This would result in the storage not needing a permit for environmentally hazardous activities according to the Environmental Assessment Regulation. The storage could, as mentioned earlier, be imposed with a permit obligation pursuant to ch. 9 s. 6a of the EC if the activity entails a risk of significant pollution or other significant harm to human health or the environment. It is likely that the authorities will impose a permit obligation for hydrogen storage because of the risk of explosion.
When examining permits for environmentally hazardous activities, one of the first step is about the suitability of the intended location. The rules on this are contained in ch. 2 s. 6 of the EC, in the basic and special provisions concerning the management of land and water areas in ch. 3-4 of the EC., and in the Planning and Building Act (2010:900). The site selection principle in ch. 2 s. 6 of the EC is designed so that the proposed or existing location of the business shall be compared with other possible sites. These options shall have been raised in consultations and environmental impact assessments.[6] The site shall be chosen considering that the purpose shall be achieved with the least intrusion and inconvenience to human health and the environment. The best possible location shall be chosen unless it appears unreasonable.[7] The choice of location must also be in accordance with the EC's management provisions[8], national interests[9], the general consideration rules[10] and EQS[11]. These rules have already been examined in this case see section *Concession under the ACP*.

Where available, salt caverns are considered the most suitable large-scale hydrogen storages. In Sweden, there are no salt caverns, instead, for large-scale hydrogen storage LRC is the technique

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[1] Prop. 2021/22:153
[2] Ch 1 s. 2 of the Electricity Act and art. 2.59 Directive (EU) 2019/944 of the European parliament and of the council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU.
[3] Art 2.60 Directive (EU) 2019/944 of the European parliament and of the council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU.
[4] Prop. 2021/22:153, p. 9 and 131.
[5] Prop. 2021/21:153 p. 131.
[6] See ch. 6 of the Environmental Code.
[7] Ch. 2 s. 7 the Environmental Code.
[8] Hushållningsbestämmelserna.
[9] Riksintressen.
[10] Hänsynsreglerna.
[11] Miljökvalitetsnormer.

presently under development. Given the large land intervention that may be required, site selection is important and by avoiding sensitive and important areas for animals and nature, the permit process is greatly simplified.

Summary for hydrogen storage

For the permit requirements for a hydrogen storage, it could be argued that a concession is not needed for a hydrogen storage since the NGA is not applicable for pure hydrogen storages. This also means that the market limitations in the NGA are not relevant for the operator. However, the revised electricity act contains provisions regarding market limitations for energy storage facilities, and in the government bill, the legislator notes that a hydrogen storage can in fact be considered an energy storage. This shows how closely entangled hydrogen is with both the electricity and the gas systems, and why hydrogen may need its own system of rules that harmonize with other legislation. The uncertainty surrounding a hydrogen system, and in this case hydrogen storage, can be problematic for operators as well as for authorities and may result in lengthy permit processes.

3.3.3 The hydrogen production facility

According to chapter 21 section 5 in the Environmental Assessment Regulation, a hydrogen production plant is subject to permit duty B which means that the operator must apply for a permit for environmentally hazardous activities to the County Administrative Board (The Environmental Assessment Delegation). The production facility will also need a permit for water operations, if the water needed comes from a natural water source and not from the municipality water. Requirements relating to both permits have been discussed in detail above and this will not be repeated here. In addition, the production facility must comply with the Seveso act and will need a permit according to the Flammable and Explosive Goods Act.[1]

3.4 The power transmission case

For the industries in northern Sweden planning for hydrogen usage on a large scale, wind power is seen as the most important source for the required energy.(SWECO, 2022) The Swedish proposal for Hydrogen Strategy, published in November 2021, also concludes that wind power is assumed to be the largest added electricity production source for the introduction of hydrogen production.(Swedish Energy Agency, 2021b) However, it is also stated that the possibilities for developments of wind power, similar to grid expansion, are affected by many different factors, e.g. permit processes, local acceptance, and co-existence with other values, such as nature and national defense, and, not the least, grid capacity.

3.4.1 Wind power plants

For the industries in northern Sweden planning for hydrogen usage on a large scale, wind power is seen as the most important source for the required energy.(SWECO, 2022) The Swedish proposed Hydrogen Strategy, published in November 2021, also concludes that wind power is assumed to be the largest added electricity production source for the introduction of hydrogen production.(Swedish Energy Agency, 2021b) However, it is also stated that the possibilities for developments are affected by many different factors, e.g. grid capacity, permit processes, local acceptance, and co-existence with other values, such as nature and national defense.

The establishment of wind power is regulated by laws and regulations depending on where it is placed.(Statens Offentliga Utredningar, 2021) Relevant to this report is the large facilities which means wind power parks. They could be either onshore or offshore. The general legislation is presented below, but besides this, investigations in accordance with Natura 2000 Chapter 7 Article

[1] S. 16 of the of the Flammable and Explosive Goods Act.

28a in The Environmental Code, as well as Article 12 of the Habitats Directive and Article 5 of the Birds Directive could be of relevance.

An onshore large park is specified in a few different ways, the wind power plants are either in a group of two or more with a height of more than 150 meters including rotor blades, or seven or more plants with a height of more than 120 meters. Onshore large parks require a permit in accordance with the Environmental Code and the municipality's approval (see below). Permits under the Environmental Code are reviewed by the County Administrative Board.[1]

Offshore power plants within inland waters or the maritime territory's boundary in the sea, as defined by:

”Sweden's maritime territory includes internal waters and the territorial sea. It is delimited against the maritime territories of other states in accordance with agreements on the national border. Inland waters include water areas on land and in the sea within the national border. The territorial sea extends 12 nautical miles (about 22.2 kilometers) from the coast.”[2]

requires a permit for environmentally hazardous activities and water operations, in accordance with Chapter 9. and Chapter 11. The Environmental Code, as well as the municipality's approval – municipal veto. Permits are normally reviewed by the court “Mark- och Miljödomstolen”. In addition to this, permits are required under the Act “Kontinentalsockellagen” (1966:314) to investigate the seabed and the closure of pipelines.

Within the Swedish economic zone, as defined by:

“Outside Swedish maritime territory, i.e. more than 12 nautical miles from the coast. The Swedish economic zone borders the economic zone of another State.”,[3]

according to section 5 of the Act (1992:1140) on Sweden's economic zone, permission is required by the Government for the construction and commercial use of plants and other establishments. In the case of a permit examination, Chapter 2–4, Chapter 5. Section 3 and Chapter 16. Section 5 of the Environmental Code applies. The application must contain an environmental impact assessment that must be produced in accordance with the rules in Chapter 6. the Environmental Code. In addition to this, permits are required under the Act “Kontinentalsockellagen” (1966:314) to investigate the seabed and the closure of pipelines.

3.4.2 Electrical power transmission grid

Production of renewable hydrogen by electrolysis is a process that requires large amounts of renewable electricity. A large part of the hydrogen demand, and thus the electricity demand, is expected to arise in bidding zone SE1, i.e. Norrbotten and northern Västerbotten, due to hydrogen-based iron ore production. While the electricity grid in northern Sweden is well-dimensioned to solve today's electricity needs, it must be expanded to meet the needs of the future. (STIMO, 2021; Svenska Kraftnät, 2021b)

The current process for domestic grid expansion is briefly described below and a more detailed description can be found in a report from 2022, which was produced on behalf of the Energy Market Inspectorate as part of the government assignment.(Sonder AB, 2022) The process for cross border projects is similar, but the government is the decision-making authority and therefore partly replaces the Swedish Energy Inspectorate upon deciding on the network concession.

[1]http://www.energimyndigheten.se/fornybart/vindkraft/vindlov/planering-och-tillstand/stora-anlaggningar/
[2] http://www.energimyndigheten.se/fornybart/vindkraft/vindlov/planering-och-tillstand/svenskt-vatten/
[3]http://www.energimyndigheten.se/fornybart/vindkraft/vindlov/planering-och-tillstand/svensk-ekonomisk-zon/

The process can be divided into five steps. The first step is a **network investigation** carried out by the network owner when they have received a request for a connection. This is an internal process, and the required time is likely to vary depending on the network owner.

The second step is **consultation** where network owners examine and decide on route and execution in terms of land access and technology, defines the design of and compiles an EIA and compiles a concession application. Concession is a form of permit that gives the holder certain rights and responsibilities within the scope of the concession and as a result also a stronger stance against competing interests. The expected time spent in this phase is between six months and two years.

The third step is a **network concession** which consists of processing the concession application with the Swedish Energy Inspectorate, notification of decisions on a network concession, and access for a land survey. Once the decision has been notified, there is an opportunity for stakeholders to appeal to the Land and Environmental Court. About 25 percent of all decisions are appealed, mainly by landowners. The time spent in this phase is highly dependent on the workload at the Swedish Energy Inspectorate, but the estimated time spent in this phase is between nine months and two years. If the connection is cross border the government is the decision-making authority and therefore replaces the Swedish Energy Inspectorate in step seven in the figure below.[1]

The fourth step is **projecting** and means that the construction is prepared. The network owner compiles and applies for necessary permits and exemptions, such as environmental action plans, coastal protection and species protection, these are handled by the relevant authority, which then notifies the network owner. In this phase, the network owner must also secure his access to the land, this is preferably done by the network owner signing a land lease agreement (which is a civil agreement contract) with the affected landowners. If this fails, the network owner will instead apply for rights of way with the Swedish Mapping, Cadastral and Land Registration Authority (Lantmäteriet). All decisions can be appealed and Lantmäteriet assesses appeals of right of way relatively often. When the network owner has gained access, the line is delineated, an environmental action plan is compiled, and contractors are procured.

The fifth and last step is **construction** which except for the construction itself also includes registration of land lease agreement if there is any, and to manage any damage that occur during construction. The latter includes to assess any damages and reimburse affected stakeholders. If there is a land lease agreement the network owner or the contractor assess the damages without involvement from authorities. If no agreement has been made, Lantmäteriet assess the proper reimbursement.

3.5 Regulatory framework for use of hydrogen

In water electrolysis, electric power splits water molecules (H_2O) into (green) hydrogen (H_2) and oxygen (O_2) gas. This section aims to list a relevant, but not exhaustive, overview of laws, regulations, and legal aspects for design of hydrogen production plants, operations, distribution, and use of hydrogen and oxygen. The following is not a complete list for the management of hydrogen and oxygen. For the safe use of hydrogen and oxygen, current standards and best practices must also be followed, which are only partially stated here. To a large extent, the regulatory framework is similar for use of hydrogen and oxygen, respectively. Parts of this section is based on a similar description for oxygen, which in its whole has been translated from a report originally in Swedish(Lindborg et al., 2022) and is available in Appendix 1.

3.5.1 EU regulations

There is a wide range of laws, regulations, recommendations, guidelines, and standards for how hydrogen should be handled. The ambition is to cover how the gas may be handled for production, storage, and transmission. In this report, hydrogen is only treated in its gaseous form. To know which

[1] 4 § ellag (1997:857)

rules to apply, a clear picture of how the hydrogen is intended to be used is needed. Furthermore, Authorities use different denotations and categories to characterize a substance and its properties. Here, following the legal pyramid, see Figure 5 later in this chapter, first the EU-regulations and then the related directives, followed by national laws, regulations, and instructions are described.

REACH and CLP

The EU-regulations on “Registration, Evaluation, Authorisation and Restriction of Chemicals” (REACH) (EC 1907/2006) and “Classification, Labelling and Packaging of substances and mixtures” (CLP) (EC 1272/2008) are on EU-level managed by the European Chemicals Agency (ECHA) and on Swedish national level by “Kemikalieinspektionen”.

REACH is a regulation adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals, while enhancing the competitiveness of the EU chemicals industry. In principle, REACH applies to all chemical substances; not only those used in industrial processes but also in our day-to-day lives. REACH places the burden of proof on companies. It impacts on a wide range of companies across many sectors, even those who may not think of themselves as being involved with chemicals. Companies need to register their substances and to do this they need to work together with other companies who are registering the same substance. REACH applies in general if you have one of these roles:

- Producer for domestic or for export inside or to outside of EU.
- Importer.
- Downstream user
- Distributor

CLP Regulation is an international system for the classification of hazardous substances. Among other things, the CLP Regulation states which warning signs to use for a substance.

“CLP is legally binding across the Member States and directly applicable to all industrial sectors. It requires manufacturers, importers or downstream users of substances or mixtures to classify, label and package their hazardous chemicals appropriately before placing them on the market.

One of the main aims of CLP is to determine whether a substance or mixture displays properties that lead to a hazardous classification. In this context, classification is the starting point for hazard communication.”

The SEVESO Directive

The Seveso Directive (2012/18/EU) has been developed by the EU and legislated in Sweden as the Act on Measures to Prevent and Limit the Consequences of Serious Chemical Accidents1999:381), briefly mentioned earlier in this chapter. The Seveso Act may become relevant when large quantities of hazardous substances are managed. Seveso aims at preventing and limiting the consequences of serious chemical accidents. The legislation sets lower and higher requirement levels for various hazardous substances. If the requirement levels are exceeded, special measures must be introduced, such as the preparation of accident action programs. Both hydrogen and oxygen are covered by the Seveso Act l and a summarizing rule applies which says how large quantities of certain substances can be stored together.

Pressure Equipment Directive

The Pressure Equipment Directive (PED) (2014/68/EU) is an EU directive and applies to the design, manufacturing, and conformity assessment of stationary pressure equipment with a maximum allowable pressure greater than 0.5 bar. PED enables import and export within the entire EEA area (27 EU countries, Norway, Iceland, Lichtenstein). The Swedish Work Environment Agency's implementation of the European standard is called AFS 2016:1.

3.5.2 Swedish regulations

EU regulations need strict implementation on a national level. An EU-directive can be implemented as a national law. The law is clarified in ordinances and specifies what is stated in the law. In the Swedish Constitutional Collection (SFS), laws, regulations and certain authority regulations are promulgated. Also, messages, so-called announcements, may be inserted if they should come to public notice and if they cannot conveniently be left in any other form. In Table 2, some examples on hydrogen relevant laws and corresponding ordinances can be found.

Table 2. Examples of Swedish relevant laws and regulations regarding hydrogen.

Classification	Title (Swedish)	Type	Published	Altered by
SFS (2010:2011)	Lag (2010:2011) om brandfarliga och explosiva varor	Lag	2010-07-11	SFS (2020:903)
SFS (1999:381)	Lag (1999:381) om åtgärder för att förebygga och begränsa följderna av allvarliga kemikalieolyckor	Lag	1999-05-27	SFS (2015:233)
SFS (2010:1075)	Förordning (2010:1075) om brandfarliga och explosiva varor	Förordning	2010-07-15	SFS (2020:790)
SFS (2015:236)	Förordning (2015:236) om åtgärder för att förebygga och begränsa följderna av allvarliga kemikalieolyckor	Förordning	2015-04-23	SFS (2018:1847)

The Swedish Civil Contingencies Agency - MSB

The Swedish Civil Contingencies Agency (Myndigheten för Samhällsskydd och Beredskap, MSB) is a Swedish authority responsible for questions about protection against accidents (act 2003:778) on protection against accidents (LSO), crisis preparedness and civil defense, in areas where no other authority has the responsibility. A legal act may contain provisions that the government or the authority that the government determines may issue regulations (authorization). When ordinances and regulations are written, they must stay within the framework of what the laws state. This means that regulations specify more precisely what is stated in the laws. For storage of hydrogen in lined rock caverns, MSB regulation MSBFS 2020:1 is found to be most related, although the regulations do not cover rock caverns. When applying for a permit for a facility, the old rules SÄIFS 2000:4 - Regulations and general advice on cisterns, gasholders, rock caverns and pipelines for flammable gas are probably more applicable to lined rock caverns. However, SÄIFS 2000:4 does not provide any detailed rules; rather, requirements such as ”Rock caverns containing air must be put into operation in a safe manner” and ”A contingency plan for emergency situations when filling must be drawn up”. At the MSB homepage, the following can be read regarding approval of permitting according to the Flammable and Explosive Goods Act:

“The permit authority may, in connection with the permit review, decide that the facility must be inspected before it is put into operation. This must be stated in the permit decision. The inspection enables checking that a completed facility meets the requirements of the legislation. The inspection focuses on whether the facility was actually built according to the information reported and accepted during the permit review and whether the facility meets current rules and the conditions set in the permit. The supervisory authority documents its observations in a service note as information for the operator. The business may not begin before the inspection has taken place, but then the operator decides himself when the handling of flammable or explosive goods begins. If the supervisory authority discovers serious deficiencies during the inspection, it can open a supervisory case, and then order that the deficiencies be remedied or prohibit the operation. The business operator can then appeal in the usual way.”

However, there are no existing standards to use for the inspection procedure of a hydrogen pipeline or lined rock cavern. MSBFS 2009:7 is the constitution on natural gas pipe systems. The related instruction is “Naturgassystemanvisningar” (NGSA) 2018 (SIS HB 325). This is under revision to NGSA 2022 including up to 5% of hydrogen. The need for a similar standard for hydrogen (VGSA) has already been identified and its preparation is planned to start as soon as NGSA 2022 is finalized. (Lidström, 2022) It is unclear if lined rock caverns for hydrogen will be included in that work.

Table 3. Examples of regulations relevant for hydrogen. Also, a constitution for natural gas as a possible base for development of additional need of hydrogen regulations.

Classification	Title (Swedish)	Type	Published	Altered by
SRVFS 2004:7	Föreskrifter om explosionsfarlig miljö vid hantering av brandfarliga gaser och vätskor	Föreskrift	2004-03-17	
MSBFS 2010:4	Föreskrifter om vilka varor som ska anses utgöra brandfarliga eller explosiva varor	Föreskrift	2010-09-01	MSFBS 2018:12
MSFBS 2011:3	Föreskrifter om transportabla tryckbärande anordningar	Föreskrift	2011-06-30	
MSBFS 2013:3	Föreskrifter om tillstånd till hantering av brandfarliga gaser och vätskor	Föreskrift	2013-10-01	
MSBFS 2015:8	Föreskrifter om åtgärder för att förebygga och begränsa följderna av allvarliga kemikalieolyckor	Föreskrift	2015-06-01	
MSBFS 2020:1	Föreskrifter om hantering av brandfarlig gas eller brandfarliga aerosoler	Föreskrift	2021-08-01	
MSBFS 2020:9	Föreskrifter om transport av farligt gods på väg och terräng (ADR-S)	Föreskrift	2020-01-01	
MSBFS 2009:7	Föreskrifter och allmänna råd om ledningssystem för naturgas	Grund-författning	2010-01-01	

The Swedish Work Environment Authority

The Swedish Work Environment Agency's statutory collection (AFS) consists of many regulations containing rules and general advice that clarify the related act. In Table 4, are some examples on regulations relevant for hydrogen.

Table 4. Examples of relevant hydrogen regulations from the Swedish Work Environment Agency.

Classification	Title (Swedish)	Type	Published	Altered by
AFS 2006:8	Provning med över- eller undertryck (AFS 2006:8)	Föreskrift	2007-01-15	AFS 2011:5 AFS 2014:34 AFS 2020:8
AFS 2016:1	Tryckbärande anordningar (AFS 2016:1)	Föreskrift	2016-05-09	
AFS 2017:3	Användning och kontroll av trycksatta anordningar (AFS 2017:3)	Föreskrift	2017-07-07	AFS 2019:1 AFS 2020:10

3.5.3 Supporting organisations

Swedish Institute for Standards

The Swedish Institute for Standards **(**SiS) is an organisation that publishes Swedish standards for industry and private use. It is a non-profit association that is part of ISO and CEN, a network of experts working to create international standards. With us, actors can take initiatives for standardization that promotes Sweden's competitiveness and provides smart and sustainable social development. If a regulation refers to a standard it can be mandatory to follow. In Table 5, some hydrogen relevant standards are listed.

Table 5. Examples of hydrogen relevant standards from SiS.

Classification	Title (Swedish)	Published
STD-80034536	Gas infrastructure - Consequences of hydrogen in the gas infrastructure and identification of related standardisation need in the scope of CEN/TC 234	2022-04-04
STD-80035758	Basic considerations for the safety of hydrogen systems (ISO/TR 15916:2015, IDT)	2022-06-01
STD-80037519	Hydrogen fuel quality - Product specification (ISO 14687:2019, IDT)	2022-08-25

Energigas Sverige

Energigas Sverige is an industry organisation for players in biogas, vehicle gas, liquefied petroleum gas, natural gas, and hydrogen. It acts as the industry's spokesperson and is the point of contact between its members and decision-makers, the media, business, and the public. It is mentioned to be acting as a secretariat for the upcoming work, VGSA (hydrogen system guidelines) chaired by Nordion Energi and driven by SIS/TK 289.

Table 6. Examples of guiding standard and guideline for developing corresponding documents for hydrogen.

Classification	Title (Swedish)	Published
EGN	Energigasnormer (EGN) 2020	2020
NGSA (SIS HB 325)	NGSA 2018 Naturgassystemanvisningar	2018

Swedish handbooks

There are several manuals and documents that are intended to help interpret rules and teach best practices. These are often issued by the same authorities that issue the regulations. In Table 7, some hydrogen relevant handbooks are listed.

Table 7. Examples of Swedish handbooks related to hydrogen.

Title (Swedish)	Published by
Hantering av brandfarlig gas för yrkesmässig verksamhet	MSB
Tillstånd till hantering av brandfarliga gaser och vätskor	MSB
Handbok för riskanalys	MSB (räddningsverket)
Räddningsverkets handbok om explosionsfarlig miljö vid hantering av brandfarliga gaser och vätskor	MSB (räddningsverket)
SEK Handbok 426 - Klassning av explosionsfarliga områden - Områden med explosiv gasatmosfär	Svensk Elstandard

European Industrial Gases Association

The European Industrial Gases Association (EIGA) is a technology- and safety-oriented organisation consisting of a consortium of several European and non-European companies that produce gas for industry and healthcare. EIGA does not issue official standards but cooperates with organisations for standardization and regulations. EIGA has published several documents on the safe handling of hydrogen and oxygen. Some of these are summarized in Table 8.

Standards for Hydrogen quality

The European Association for the Streamlining of Energy Exchange – gas (EASEE-gas) has published a Common Business Practices (CBP) hydrogen quality specification.[1] This CBP defines the recommended quality specification for non-blended hydrogen. The standard sets a minimum requirement of hydrogen at 98 mol% and a maximum of hydrocarbons, including methane, at 1.5 mol%. The relatively low hydrogen purity, compared to hydrogen from water electrolysis, is set due to EASEE-gas expectations that the large-scale production of hydrogen, in Europe before 2030, will be based on hydrocarbons (i.e. grey or blue hydrogen). Another reason mentioned is that the industry (which have lower requirements for purity than e.g. fuel cells in transport) will use the large part of the hydrogen. This CBP standard will, in contrast to green hydrogen, not meet the fuel cell standard ISO 14687:2019, mentioned earlier in this chapter. The hydrogen quality standard is obviously very important to keep in mind for the design of a hydrogen pipeline with feed in from different producers and connected consumers, which will require measures for quality control and guarantees.

[1] CBP 2022-001/01, Hydrogen quality specification.

Table 8. EIGA's recommended reading for safe handling of hydrogen and oxygen.

Code	Title
IGC Doc 15/06/E	Gaseous hydrogen stations
DOC 235 / 21	Industrial Gas Pipeline Integrity Management
DOC 121 / 14	Hydrogen Pipeline Systems
PP 45 / 22	Position Paper on Gas Markets - EIGA Position Paper on the Hydrogen and Decarbonized Gas Market Package
NL 79	The hazards of oxygen enriched atmospheres
TP 12	Fire hazards of oxygen enriched atmospheres
Doc 4	Fire Hazards of Oxygen and Oxygen Enriched Atmospheres
Doc 10	Reciprocating Compressors for Oxygen Service
Doc 13	Oxygen Pipeline and Piping Systems
Doc 27	Centrifugal Compressors for Oxygen Service
Doc 33	Cleaning of Equipment for Oxygen Service
Doc 154	Safe Location of Oxygen and Inert Gas Vents
Doc 200	The Safe Design, Manufacture, Installation, Operation and Maintenance of Valves Used in Liquid Oxygen and Cold Gaseous Oxygen Systems.
Info 15	Safety Principles of High-Pressure Oxygen Systems

3.6 Swedish regulations under development

The results from the scenario analysis of current legislation here, together with the knowledge obtained in the previous chapter and the workshops, reveal several areas where regulations need to be developed in order to facilitate the establishment of a hydrogen system. Fortunately, many of those issues have been identified before and in some areas the regulations and processes are already under revision and development. In this section, current developments relevant to the hydrogen system are described. Since the field is moving fast, it is important to keep in mind that this report was prepared in Aug. 2022. First, developments regarding the process for expansion of infrastructure for electrical power are described. Then, revisions of EU legislation are presented, together with a summary of most relevant policy instruments.

Wind power and the municipal veto

The total Swedish power production in 2020 was ca. 165 TWh, whereof ca. 67 TWh came from hydro, 60 TWh from nuclear, and 28 TWh from wind power. By 2025 wind power is expected to reach ca. 50 TWh.(Infrastrukturdepartementet, 2022) The goal of the Swedish Hydrogen Strategy of 15 GW by 2045 of electrolysis capacity corresponds to an electricity requirement of ca. 100 TWh per year (at an average capacity factor of 76%) and places demands on both production and dimensioning of the electricity grid on regional and transmission level.(Swedish Energy Agency, 2021b)

The Swedish Energy Agency and the Swedish Environmental Protection Agency adopted, in January 2021, a national strategy for a sustainable wind power expansion.(Energimyndigheten, 2021) The strategy concluded the need until year 2040 of 100 TWh of new wind power electricity and expected 80 TWh of that to be onshore. In June 2022, the plans for grid connections to offshore wind power mention that possibly 100 TWh could be provided from offshore,(Svenska Kraftnät, 2022a) although the first round of connections are expected to provide 20-30 TWh by 2035.(Infrastrukturdepartementet, 2022)

Swedish municipalities are obliged to general and detail plans for the physical use of their land and water areas. The general plans are reviewed by the region boards in order to investigate how the plans handle national interests, e.g. energy production. Previously, detail plans were required for wind power plants (if the diameter of the rotor was larger than 2 m). Nevertheless, it happened that municipalities that did not want wind power establishments neglected to develop the needed detail plan. Hence, in 2008, a government investigation suggested to remove previous demands for detail plans for wind power. However, the government considered that to be a too large intervention on the municipalities autonomy and added the municipality's approval to the proposals suggested by the investigation, without an external investigation of the effects.(Statens Offentliga Utredningar, 2021) Hence, according to current regulation, a municipality's political decision may stop applications for permission at any time until the permit has gained legal force, even if the municipality has previously approved the application.(Statens Offentliga Utredningar, 2021)

In a study for the Swedish wind energy association in 2022, the reasons for rejections are presented.(Svensk Vindenergi, 2022) Out of 148 applications for 2540 wind power plants seeking permit onshore between year 2014-2019, 55% were rejected (partly or only) due to the municipal veto. In 2021, 22% of the onshore wind power plants were given a permission permit in accordance with the Environmental, and out of the 454 plants not given permission 170 were stopped by the municipal veto.

For offshore wind power plants who sought permission and was decided upon between 2014 and 2021 by first instance, 6 out of 7 projects were rejected, of which 2 were rejected by means of the municipal veto. There are other projects who have not been decided upon yet.

Looking closer at the relevant regions for the purpose of this prestudy; Norrbotten, Västerbotten, Västernorrland, and Gävleborg; the details for the years 2014–2021 are shown in Table 9.

Table 9. Number and share of approved wind power plants 2014-2021 per region. (Svensk Vindenergi, 2022)

Region	Norrbotten	Västerbotten	Västernorrland	Gävleborg	Sweden
Individual wind power plants decided upon	347	853	1 169	390	5 455
Number of approved plants	183	427	713	126	2 449
Number of denied plants	164	426	456	264	3 006
Share of approved plants	53%	50%	61%	32%	45%

In March 2022, a bill was submitted by the Government proposing that the municipality still should have the right to say no to wind power establishments, in accordance with current legislation on the municipal veto. However, changes were proposed to when the municipality needs to do so – this was proposed to be at an earlier stage in the planning phase. The bill also proposed changes to what the municipal position statement should contain. However, the bill was rejected in the Swedish Riksdag on June 22nd, 2022. Related to this, a government investigation will in March 2023 provide proposals for compensations to improve the social support of expanded wind power and overcome the “Not in My Backyard” (NIMBY) problem.

The process of grid expansion

The process of expanding the electricity grid can currently take between 7 and 15 years, depending on the project's circumstances (Sonder AB, 2022). Long and uncertain lead times risk becoming an obstacle for future hydrogen projects and other electrification projects. This has attracted the attention of e.g. the Committee for Technological Innovation and Ethics (Komet), which has therefore formulated a joint government assignment to develop new working methods to better coordinate the authorities' respective parts of the permit process. The goal is to streamline the permit process work more in parallel processes to shorten lead times into half in order to promote electrification. (Infrastrukturdepartementet, 2022) The assignment runs until May 2023.

The Swedish power transmission system operator (TSO) Svenska Kraftnät (SvK) started in 2022 an investment program, Fossilfritt övre Norrland (FÖN), to enable the transition of the industry. It is part of a pilot project to shorten the lead times for grid expansion and aim to work with several phases in parallel, in order to complete the first two steps and obtain a compiled concession application in 3 years (instead of 6–7 years today). (Svenska Kraftnät, 2022b)

SvK together with the Finnish TSO, Fingrid, in 2016 started planning a new 400 kV transmission line between Messaure in Sweden via Isovaara to Pyhänselkä in Finland, the Aurora Line. The project has by EU been granted a Project of Common Interest (PCI) status, which enables an accelerated permit process and eligibility to apply for financial assistance from the Connecting Europe Facility (CEF) financial instrument. The EU has granted 50% CEF funding for the planning and environmental impact assessment of the project and CEF funding for the construction phase will be applied for.(Fingrid, 2021) The Aurora Line is expected to be finalised and come into service by 2026 and will increase the electricity trading capacity between SE1 and Finland by 800 MW to 2000 MW.(Svenska Kraftnät, 2021b)

As a part of FÖN, mainly to provide electrical power to HYBRIT, grid expansion to Vitåfors from either Porjus or Messaure is being planned for, with the aim to be completed by 2026. Furthermore, the government has approved for SvK to invest 8.4 billion SEK to strengthen the grid at several positions around Norrlandskusten to enable 2000 MW in additional capacity by 2030.(Svenska Kraftnät, 2022b)

However, as discussed in next chapter, this addition may not cover the expected capacity need between SE1 and Finland from 2030, assuming that a large share of the available wind power production will be in Finland. To facilitate a greater electricity trading capacity between SE1 and Finland it may be necessary to construct additional transmission lines which, will need a repeated process.(Fingrid, 2021)

In January 2022, SvK were given the instruction to build the transmission network within Sweden's maritime territory, to enable the connection of offshore electricity production. The grid connection fee, as share of the costs for an offshore wind power project, is about 15-30%, hence, the possibilities for new projects would be improved.

In the first stage, six prioritized offshore grid connection points are proposed.(Svenska Kraftnät, 2022a) For this project it is most relevant there is also an ongoing investigation of a connecting point in Gulf of Bothnia between Malören and Pite-Rönnskär, allowing at least 1,400 MW. Also, the southern Bothnian Sea is suggested to have a grid connecting point, preliminary in the area between Hudiksvall and Axmar, for at least 1400 MW. These will also benefit from the reinforcements being planned for the land-based transmission network, e.g. within FÖN. This is in parts, a prerequisite to provide the offshore grid connecting points. Out of the six proposed grid connecting points the two projects mentioned above has the lowest priority, and the goal is to provide the transmission capacity in these areas by 2033 to 2035.

For each offshore connecting point, a pool for interested stakeholders will be established and published, to enable interaction between the actors. Currently there are applications for grid connection for 22 GW within the Gulf of Bothnia, and those projects within the proposed geographic area will have the possibility to become part of the pool where the costs for offshore connection will be socialized. Also, the current process, where the actors cover the costs for connection to the land-based grid, will remain, although it will be developed to better suit large-scale offshore wind power.(Svenska Kraftnät, 2022a)

3.7 Key EU documents

In this section, we introduce key EU documents of importance for the Swedish hydrogen system, and how they relate to each other. First, some key wording is introduced and described as they are commonly used within EU documents.[1]

- **What is a strategy?**

  A Strategy defines the plan for how to achieve a given goal.

- **What is a policy?**

  Policies are rules, guidelines, principles, or frameworks that are adopted or designed by an actor to guide decisions, achieve rational outcomes or long-term goals. A policy is a statement of intent and is implemented as a procedure or protocol. Policies are formulated to direct and influence decisions and keep activities within a set of established boundaries. The term may apply to government, public sector organisations and groups, as well as individuals

- **What is a policy instrument?**

  Policy instruments are tools which can be used to overcome problems and achieve specific objectives. Often, one instrument is designed to reinforce the benefits of one another instrument to achieve synergy or complementarity. Policy instruments include, for example regulations, economic transfers, and soft instruments, such as voluntary standardizations and code of conducts.

- **What is a regulatory framework?**

  Regulatory frameworks can include procedures, regulations, guidelines, codes of conduct and other regulatory documents

- **What is the difference between EU directives and regulations?**[2]

  An EU directive is a legal act that sets out a goal that all EU countries must achieve. However, it is up to the individual countries to devise their own laws on how to reach these goals. An EU regulation, on the other hand, is a *binding legal* act. It must be applied in its entirety across the EU.

[1] https://ec.europa.eu/info/strategy_en

[2] https://ec.europa.eu/info/law/law-making-process/types-eu-law_en

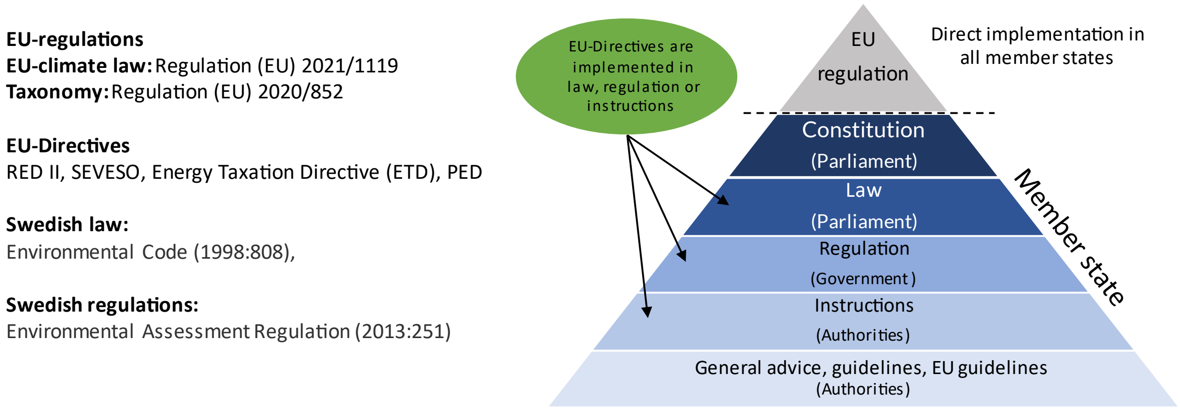

Figure 5. A schematic hierarchy of EU regulations and directives relative to national laws and regulations etc.

The EU regulations and directives are, of course, related to each other. Due to new or updated strategic plans (e.g. the European Green Deal, the Fit for 55 Package etc.) or climate goals, several of them need to be revised, which in turn could imply the need for new or changed Swedish laws and regulations. Some of the key documents, and their relation, for hydrogen in an energy system are shortly presented in this section.

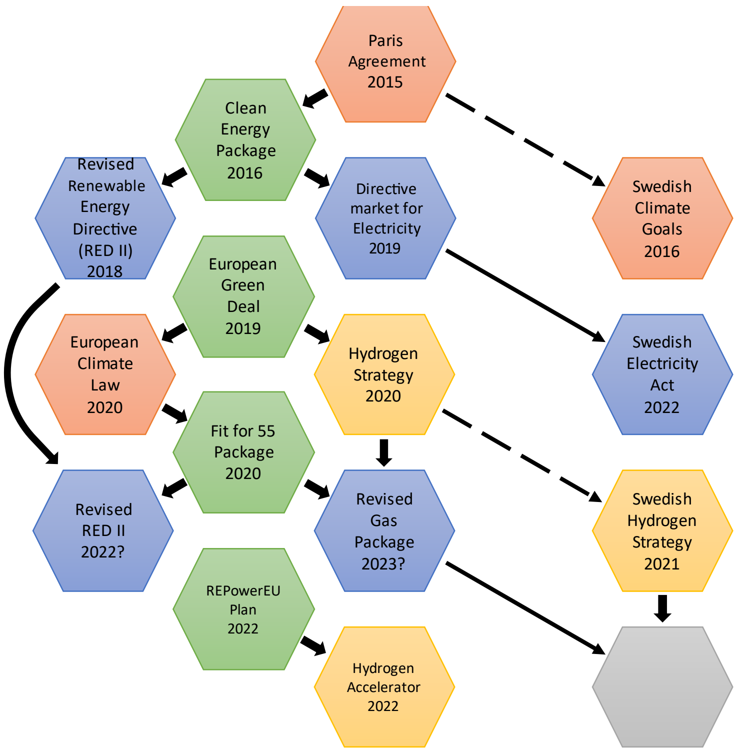

Figure 6. Schematic of the relation between climate laws (red), packages (green) of regulations and directives (blue), and strategies (yellow) together with the year they were introduced. The grey area indicates gaps in Swedish regulations for a hydrogen system.

Clean Energy Package

The Clean energy for all Europeans package was launched in 2016 and implemented in 2019. The package addresses all pillars to implement the energy union strategy published in 2015 and consists of a new set of four regulations and four directives to ensure continued transition and reach the goals stipulated in the Paris Climate Agreement from 2015 and the EU strategy of carbon neutrality by 2050.

The package was implemented when the Council of ministers of the EU formally approved the last four out of eight thereby future proofing the European electricity market.(Office of the European Union, 2019) The four parts that were implemented in 2019 are the Directive on common rules for the internal market for electricity (2019/944), the Regulation on the internal market for electricity (2019/943), the Regulation on risk preparedness in the electricity sector (2019/941), and the Regulation (2019/942) establishing an EU Agency for the cooperation of energy regulators (ACER). An EU regulation applies in in all member states regardless of national laws and regulations, an EU directive is a set of rules that sets objectives to be achieved but leaves it to the Member States to formulate their own detailed national laws and regulations. Member states are continuously working on implementing the new directives and regulations in national law.

The European Green Deal

The European Green Deal (2019/640) is a new growth strategy, presented in Dec. 2019, that aims into a fair society with a resource-efficient and competitive economy, where there are no net emissions in 2050 and economic growth is decoupled from resource use. To deliver this, and ensure effective carbon pricing throughout the economy, all relevant climate policy instruments are revised. Relevant for the scope of this report are, but not limited to:

The European Climate Law

The European Climate Law in 2020 writes into law the long-term target to become climate-neutral by 2050 for EU countries as a whole and sets the intermediate target of reducing emissions by at least 55% by 2030, compared to 1990 levels.

EU Hydrogen Strategy

To achieve the European Green Deal, in the hydrogen strategy (2020/301) [1] it is recognized that hydrogen could over time offer solutions for parts of the energy, industry, and transport sectors that are hard to abate through direct electrification. The priority is to progressively develop production of hydrogen from wind and solar energy with the following objectives:

- In the first phase (2020-2024), at least 6 GW of electrolysers are to produce 1 Mt of hydrogen.
- In the second phase (2025-2030), at least 40 GW of electrolysers produce 10 Mt of hydrogen.
- In third phase (2031-2050), renewable hydrogen technologies would reach maturity with large-scale deployment and demand expected.

It is recognized that to achieve the strategic goals a strong investment agenda is required. To support this the European Clean Hydrogen Alliance was started to identify viable investment projects, including Important Projects of Common European Interest (IPCEI), along the hydrogen value chain. Furthermore, a common criterion for the certification of renewable hydrogen should be introduced.

In the first phase, production is expected to be placed close to existing hydrogen demand, e.g. in the chemical sector. Also, manufacturing of large electrolysers (up to 100 MW) needs to be scaled up. In the second phase, demand side policies, e.g. quotas or carbon contracts for difference in specific sectors, could be needed to include new applications, e.g. steel-making, and hydrogen valleys will develop based on local production and demand with transport over short distances. Also, the backbone of a pan-European grid will be planned, with the aim of an open EU hydrogen market with unhindered cross-border trade by 2030.

[1] European Commission, A hydrogen strategy for a climate neutral Europe, 2020-07-08

Fit for 55 package

The Fit for 55 package consists of a set of interconnected proposals to ensure a fair, competitive, and green transition. It includes proposals for revised or new regulations to implement the EU Climate Law, in particular to reach the improved target of reduced net greenhouse gas emissions by at least 55% by 2030 (the previous target was 40%). Relevant for the scope of this report are, but not limited to:

Revision of the Emissions Trading System

A cornerstone of the package is to build on the EU Emission Trading System (EU-ETS), which should provide a cost-effective mechanism to bring down emissions through a carbon price signal (i.e. a cost per tonne of emitted CO2), by strengthening it and gradually applying it to new sectors of transport and buildings. To remain competitive and avoid carbon leakage, a carbon border adjustment mechanism (CBAM) is proposed.

EU Taxonomy

The EU taxonomy regulation (2020/852) is a classification system of environmentally sustainable economic activities. Put simply, it is a dictionary-style tool detailing specific business activities that are considered sustainable by the EU and it is being created to help investors make green investments. The taxonomy specifies how an activity, such as manufacture of iron and steel, can contribute to environmental objectives, such as climate change mitigation and climate change adaptation, and what criteria the activity has to meet. The taxonomy fills two important needs: it provides a common language for talking about sustainability and it uses objective, quantifiable criteria for assessing businesses. The regulation entered into force in July 2020.

The EU Taxonomy sets a limit for sustainable hydrogen production of 3 tCO_2/t (including blue hydrogen and green hydrogen with a limit of 100 g CO_2/kWh for the electricity mix). It classifies manufacture of iron and steel as a ‘transitional activity’ (with a limitation for the different process steps, e.g. 1.3 tCO2e/t product for the hot metal). In short, this means that the activity must contribute to climate change mitigation and find a pathway to keeping global warming in line with Paris Agreement commitments.

Transitional activities only qualify where the following criteria are met:

- There are no technologically or economically feasible low-carbon alternatives;
- Green House Gas emission levels correspond to the best performance in the sector or industry; and
- The activity does not lead to carbon lock-in or hamper the development and deployment of low-carbon alternatives.

Revision of the Gas Package

A proposal for a hydrogen and decarbonized gas package (regulation 2021/803 and directive 2021/804) was presented in Dec. 2021 to create conditions for a shift from fossil natural gas to renewable and low-carbon gases, in particular hydrogen and biomethane. One of the main aims is to establish a market for hydrogen and enable the development of dedicated infrastructure.

As for electricity and fossil gas, hydrogen network operators and storage operators need to keep their operations independent from the production and supply of hydrogen, in order to avoid conflicts of interest. Similarly, horizontal unbundling rules require hydrogen network operators to be in legal entities that does not comprise the operation of electricity or fossil gas networks. The long-term goal is to enable universal access to hydrogen grids based on tariffs, and it is proposed that renewable and sustainable hydrogen (see below) obtain reduced feed-in tariffs by 75%. However, until 2030 Member states have the option that conditions for grid access may be negotiated between parties.

The European Network of Network Operators for Hydrogen (ENNOH) will be created to promote cross-border infrastructure coordination. Also, the proposal foresees that the national network development plans should be based on a joint scenario for electricity, gas and hydrogen; and that they should be aligned with both National Energy and Climate Plans and EU-wide Ten Year Network Development Plan.

REPowerEU

This is the European Commission's plan to move away from the dependence on Russian Fossil Fuels, well before 2030, and to speed up the clean energy transition. The aim was presented in March 2022, and shortly after the leaders of the European Council agreed to that the EU would "fully phase out its dependency on Russian gas, oil and coal imports as soon as possible". In short-term, this will be made by saving energy and diversifying supplies. In long-term, additional power from renewable energy (hence RE) while switching from fossil fuels to hydrogen and biomethane are key actions.

Hydrogen Accelerator

The REPowerEU plan, presented in May 2022 and described in the introduction of this chapter, sets the ambition for hydrogen production within the EU to 10 Mt as well as imports of 10 Mt (whereof 4 Mt in the form of ammonia), in order to enable the recommendation to increase sub-targets for RFNBOs in industry to 75% and in transport to 5%.

To accelerate investments in renewable hydrogen, additional funding of hydrogen in industry as well as an EU-wide scheme for Carbon Contracts for Difference will be available (although no details are provided for the latter). An objective is to have in place by 2025 a combined annual electrolyser manufacturing capacity of 17.5 GW (which can be compared to the current manufacturing capacity of ca. 2 GW). ACER and ENNOH will deliver preliminary trans-European hydrogen infrastructure needs within 3 hydrogen priority corridors by March 2023.

Hydrogen Corridors

Five main hydrogen pipeline corridors have been proposed by the GSO-organisation European Hydrogen Backbone.(European Hydrogen Backbone, 2022b) One of them is the North Sea corridor to transport Norwegian, Danish, and Dutch hydrogen to Germany. However, a large fraction (ca. 30%) of the hydrogen is made from fossil gas with CCS, with lowest production costs in Norway estimated to be ca. 1.6 EUR/kg (although based on conditions before the war in Ukraine). Another suggestion is the Baltic Corridor to transport hydrogen from Sweden and Finland via the Baltics and Poland to Germany. Here, the estimated production costs of hydrogen in Sweden and Finland are 2.1-2.4 EUR/kg in 2030 and 1.6-1.9 EUR/kg in 2040.(European Hydrogen Backbone, 2022b)

Revision of the Renewable Energy Directive (RED)

The current Renewable Energy Directive (RED II, 2018/2001) is EU's legal framework for the development of renewable energy. It contains all sectors and strives for the EU to be a leader in a clean energy transformation. A third revision is ongoing (unofficially called RED III), and on July 21st, 2021, the Commission presented a proposal. The Council and the European Parliament are currently considering the proposed revision and adoption is expected by the end of 2022.

The original proposal (2021/557) contained, among others, an increased EU-level target of at least 40% of renewable energy in the overall energy mix by 2030. The current share of renewables is approximately 20%. A sub-target of 2.6% Renewable Fuels of Non-Biological Origin (RFNBOs), mainly renewable hydrogen and electrofuels, by 2030 is introduced for transports. Also, member states shall ensure that the contribution of RFNBOs should be 50% of the energy content of the hydrogen used in industry by 2030. Based on current energy usage, those targets would correspond to ca. 5 Mt renewable hydrogen in transport and 5 Mt in industry.

During the current period of revision, the emerging energy crisis in Europe has led to increased ambitions to increase renewable energy within the EU. The EU parliament decided in Sep. 2022 to support a revision of the goals to at least 45% of the share of energy consumption within the EU should come from renewable energy by 2030. It is clarified that member states shall ensure that the share of RFNBOs is 50% of the hydrogen used in industry and added that by 2035 that share is at least 70%. Furthermore, the sub-targets for transport are raised to 2.6% RFNBOs by 2028 and 5.7% by 2030, and at least 1.2% of the fuel delivered to the maritime mode should be of RFNBO.

Of particular interest for renewable hydrogen is the revision of article 27(3), which defines the rules for electricity to be counted as renewable. In the current REDII, the conditions are that either the facility producing RFNBO (e.g. an electrolyser) is directly connected to the installation producing renewable electricity (e.g. a wind power plant) that comes into operation after, or at the same time as, the facility, or electricity may be taken from the grid if its renewable properties have been demonstrated (e.g. through a power purchase agreement, PPA, of the used capacity from wind power). However, it is also stated that by 31 Dec. 2021 the Commission shall adopt a delegated act setting out detailed rules to supplement the REDII.

The Commission's delegated acts

As part of this process, in May 2022, the European Commission presented drafts for two delegated acts, to clarify the definition on RFNBO (e.g. renewable hydrogen). After the consultation period, ending 17 June 2022, the finalization of the draft of the legal act will be prepared. The European Council and the European Parliament may then adopt or reject the draft. While the final delegated acts from the Commission were still under preparation, the Parliament, in Sep. 2022, voted on its position on the revision of REDII, which for article 27(3) was less strict on the requirements for electricity for RFNBOs to count as renewable, compared to the draft from the Commission.

Article 27(3) is considered necessary, since the production of hydrogen from water electrolysis to the extent aimed for require significant amounts of electricity (in the same order as the current demand of electricity for France), and that one of the key pillars in the energy transition is that direct electrification should be pursued in the applications where it is possible, and hydrogen should be focused on hard to abate sectors. Hence, to avoid RFNBOs cannibalizing on the renewable electricity needed to the transition to direct electrification (e.g. for battery electric vehicles and heat pumps); spatial, temporal, and additional correlation have been considered for electricity for RFNBOs. Spatial correlation refers to that the electricity should be produced close to the electrolyser, e.g. within the same bidding zone. Temporal correlation refers to that the electricity and the hydrogen are produced within the same period of time, e.g. preferably at periods when there is an abundance of renewable electricity produced. The additionality principle refers to that the renewable power plant should be newly installed, so that is an addition to the current capacity and thus, the hydrogen production should not cannibalize on existing renewable power.

In the draft from May 2022 of the Commission's delegated act, for hydrogen to qualify as renewable, it is stated *"In order to account hydrogen as fully renewable, the production of renewable hydrogen should therefore incentivize the deployment of new renewable electricity generation capacity (principle of additionality) or take place at times where the electrolysers support the integration of renewable power generation into the electricity system or in bidding zones where renewable electricity already represents the dominant share and adding additional renewable electricity generation capacity would not be necessary or possible."*

Hence, <u>no additionality nor correlation is needed in case:</u>

- the hydrogen production is in a bidding zone where the average proportion of renewable electricity exceeds 90% in the previous calendar year and the production of the fuel does not exceed a maximum number of hours set in relation to the proportion of renewable electricity in the bidding zone.

Although the share of RE in Sweden was 60% in 2020, it was ca. 95% in both SE1 and SE2. In contrast, the share of RE in 2020 was 27% in SE3 and 44% in Finland. Hence, renewable hydrogen could be produced from electrolysers connected to the grid in northern Sweden at a capacity factor of up to 95%.

Else, the requirements for renewable hydrogen production are:

a) The electricity production came into operation not earlier than 36 months before the installation producing the fuel. Or if electricity production is added to an existing installation – 24 months. The electricity generation plant cannot receive financial support.

b) And the production of renewable hydrogen should take place within the hour of the consumption of electricity for the production of hydrogen, and both installations should be within the same bidding zone. If they are not in the same bidding zone the electricity price in the zone generating the electricity should be equal or higher than in the zone producing the hydrogen.

c) Or the electricity price is below 20 EUR/MWh or 36% of the EU carbon price.

d) Or the electricity production is connected to the installation producing the fuel via a direct line or within the same installation.

However, in order to ramp up electrolyser capacity in short-term, the additionality principle does not apply for hydrogen production facilities installed before 2027.

In a second delegated act (DA), providing methods to assess emission-savings from RFNBOs as transport fuels, limit threshold for low-carbon RFNBO is 28 g CO2/MJ, which for hydrogen corresponds to 3.4 kg CO2/kg hydrogen. For hydrogen from electrolysers, that require an average carbon intensity of electricity of 20 g CO2/MJ (at 70% efficiency). For RFNBOs produced from grid electricity, the share of RE and carbon-intensity of power production at national level determine the emissions from the RFNBO. Hence, a grid-connected electrolyser in SE3 would produce low-carbon hydrogen due to the average 6 g CO2/MJ in the national grid, but not necessarily renewable hydrogen. In Finland, the average carbon-intensity of the grid (37 g CO2/MJ) is currently too high to produce low-carbon hydrogen, but renewable hydrogen can be produced if the hydrogen producer in Finland establishes a PPA for RE. Even if the second DA only deals with emissions from the transport fuels, the revised RED II claim that the rules to determine RFNBO's renewable nature when produced from electricity should be extended from the transport sector also to other sectors. Hence, it has been considered problematic that in the second DA not the principle of additionality nor bidding zones are considered.(Bellona Europa, 2022)

The Parliaments proposal for amendments

In Sep. 2022, the European Parliament voted on its official position on which amendments the revision of the REDII should include. As it comes to article 27(3), regarding electricity from the grid to be counted as renewable, the proposal states:

- Hydrogen fuel producers should be required to conclude one or more PPAs for RE.
- The balance between the electricity from the PPAs and the electricity taken from the grid shall be achieved on a quarterly basis.
- The installations generating the electricity under the PPAs are located in the same country or in a neighbouring country or in an adjacent offshore bidding zone as the electrolyser

Hence, the Parliament suggests that the requirements on spatial and temporal correlations are less strict than the Commision's DA, same or neighbouring country compared to same bidding zone and hourly compared to quarterly balancing, respectively, and that the additionality principle is not included. However, the Parliament makes no exemption for bidding zones with already high share of renewable energy, e.g. SE1, in contrast to the draft from the Commission.

Before the revised REDII can be finalized, there will be a trilogue with inter-institutional negotiations between the European Commission, Parliament, and Council. Given that the positions on article 27(3), at the time of writing (Oct. 2022), are not aligned between the Commission and the Parliament, it is unclear which position the Council will take and if the finalized revision of the text will be similar to one of the two current positions or, more likely, somewhere in between.[1]

The draft of the DA including the additionality principle have been intensively debated. On one hand, the rules have been claimed to be too strict and according to one study increase the cost for renewable hydrogen, i.e. from 2.8 to 4.7 EUR/kg for wind power in Germany by 1.2 EUR/kg due to the additionality principle and 0.7 EUR/kg due to spatial and temporal correlation).(Frontier Economics, 2021) On the other hand, in another study, it has been found that stricter requirements increase the costs in Germany by 2030 from 3.5 to 4.1 EUR/kg, but at the same time lead to reduced emissions at system-level, since more fossil power generation is replaced by renewable, corresponding to carbon footprints being reduced from 2.5-3.5 kg CO2/kg hydrogen to zero. (Brauer et al., 2022)

Sustainable and Renewable hydrogen

While the EU Taxonomy determines what will qualify as sustainable hydrogen, the revised RED regulates what will have the status of renewable hydrogen. Hydrogen qualifies as sustainable according to the EU Taxonomy is emission-savings from production are more than 70% compared to fossil-based production (i.e. grey hydrogen) and the limit is set to 3.0 kg CO2/kg hydrogen.

Hydrogen qualifying as sustainable could improve the disclosure of companies subject to reporting under the EU Taxonomy and its production can be supported using private capital within the context of sustainable finance. However, hydrogen qualifying as renewable under the revised RED II will be able to benefit of public support at EU level (and likely also at national level). From a Scandinavian perspective it is worth noting that the DA explicitly mention that renewable hydrogen (or electricity used to produce it) may not be derived from biomass.

The sub-target of 70% RFNBO in industry by 2035, or 75% by 2030 proposed in REPowerEU, means that a majority of a country’s hydrogen usage must meet the definition of RFNBO. Currently, the Swedish west coast chemical industry stands for 90% of Swedish hydrogen usage, ca. 7 TWh/y of non-RFNBO. It has been estimated that this demand will remain at the same level by 2030 and could be up to 14 TWh/y by 2045.(Edvall et al., 2022) In this project, the demand for hydrogen in SE1 has been estimated to 21 TWh/y by 2030 and 41 TWh/y by 2040. Hence, to reach a sub-target of 75% RFNBO by 2030, if the current non-renewable hydrogen production at the west coast in SE3 remains, all added usage in SE1 must be met by renewable hydrogen. It is therefore critical that the northern Swedish iron industry uses RFNBO.

According to the Commissions current draft of the DA, the high share of RE in SE1 and SE2 give no need to consider the principle of additionality, hence, establishments of renewable hydrogen production will be facilitated. According to the current position of the Parliament, no such exemption is made, and to use electricity from the grid hydrogen producers need to conclude PPAs for renewable electricity produced in Sweden or neighboring countries. Although electrolysers in SE1 have relatively good possibilities to conclude PPAs from wind power in Sweden or Finland, or hydro power in Sweden or Norway, the long-term structure of PPAs likely will reduce the incentives for flexible operation of electrolyser to benefit from periods of low-cost electricity due to abundant wind power and to provide stability services to the grid.

3.8 Discussion and conclusions

Hydrogen is considered a vital part in the green transition both for Sweden and the EU. In this chapter, the existing and forthcoming regulatory framework in related to the hydrogen value chain has been examined. In the analysed **hydrogen transmission case**, existing Swedish legislation has been examined and the result shows that **most things relating to hydrogen is, unfortunately, unclear**. A

[1] https://insightplus.bakermckenzie.com/bm/energy-mining-infrastructure_1/european-union-the-end-of-additionality-requirements-in-the-eu

pure hydrogen pipeline can only be given concession under the Act on Certain pipelines if the hydrogen is considered and used as fuel – if the hydrogen serves another purpose, the act will not be applicable. **The Natural Gas Act is not applicable for a pure hydrogen pipeline** at all.

This leads us to a first question – **should concession be needed for hydrogen transmission pipelines?** A concession decision is binding upon review under the Environmental Code, gives the holder certain rights and responsibilities and a stronger stance against competing interests. The legislator has seen it fit to oblige natural gas pipelines and storages with concession obligation, hence, **it would be an anomaly if hydrogen transmission pipelines and storages would not need a concession**.

The second question is, **how should the concession for hydrogen pipelines be regulated?** The obvious options seem to be to **include hydrogen in the Natural Gas Act or to create a new Hydrogen Act**. One major advantage of using the existing Natural Gas Act is of course that it would likely be relatively easy to include hydrogen, since the structure of the act already exists and the rules for system balance responsibilities and ownership are already included. Another advantage is that it is similar to the proposed EU regulation for the gas market – **hydrogen and natural gas is in the same legislative package.**

It is not only the concessions existing that is unclear from a legal perspective, **but hydrogen activities are also not listed in the Environmental Assessment Regulation**, which means that no permit obligation exists explicitly. As mentioned earlier, it is likely that the authorities will use the rule in chapter 9 s. 6a of the Environmental Code to create a permit obligation for hydrogen activities. This, however, **leaves the operators in the dark regarding what kind of permit process awaits them**. The legislator should review this and **adapt the existing legislation to include a clear permit obligation for hydrogen activities**.

Another major question is ownership and control over the hydrogen infrastructure. As of today, there are **no rules regarding hydrogen markets and ownership**. The Natural Gas Act contains rules regarding tariffs, unbundling, system balance responsibility and so on. Should these rules apply to the hydrogen system as well? In Finland, the Government has mandated the natural gas TSO, Gasgrid Finland, to develop the national hydrogen infrastructure and the hydrogen market in the Baltic Sea Region.[1]

In the proposal to the new gas market package the **EU suggests that the hydrogen market is exempt from rules regarding unbundling until the year 2031**. A similar model could be used in Sweden, but it could also be argued that the unique conditions of SE1 (no existing natural gas transmission grid and the possibility to produce renewable hydrogen without considering the principle of additionality) could benefit from other rules than EU in general, to **support (or at least not hinder) the introduction of a hydrogen system in this decade**.

Related to the process of expanding the electricity network is the network owner's ability to plan for future needs. A general concern among network owners is that actors such as regions, municipalities and large electricity users are unable to provide sufficient data on future electricity needs.(WSP, 2021) However, the **difficulties to provide future electricity needs is most understandable, given the rapid developments** (nationally and globally) of the energy system in general and hydrogen system in particular. Nonetheless, this leads to uncertain forecasts that often lack reasonable accuracy for planning which may put of investments or lead to over- or underinvestment. While this is not a regulatory hinder per se, it may be viewed as a regulatory gap as **regulation could be formed to assist actors in supplying data on future electricity needs**.

[1] Gasgrid Finland to develop a national hydrogen infrastructure – enabling the creation of new investments and jobs, and supporting Finland's energy security and self-sufficiency – Gasgrid Finland

Going forward it is likely that sector coupling between the different energy systems will become more common and the regulation must consider this integration. Hence, a **close collaboration between authorities and between actors from the different energy systems is necessary**. Thus, it is positive that Svenska Kraftnät has initiated discussions with actors within the hydrogen sector,(Svenska Kraftnät, 2021b) and that in the revised Electricity Act (from July 1st, 2022) all grid owners are obliged to develop grid development plans for the coming five to ten years. Among other things, the network development plans should include alternatives to grid expansion such as the use of demand flexibility, energy efficiency, energy storage facilities and other resources. (Energimarknadsinspektionen, 2021, 2022) As hydrogen and hydrogen production can be used as a flexibility resource, this may help strengthen the interaction between different energy systems. However, **the strong coupling between electricity and hydrogen require that more efforts should be put in place to promote collaboration** and co-planning between the electricity and gas TSOs and DSOs.

Regulation may also impact where electrolysers are located. Suppose a wind park is set to supply electricity to electrolysis to produce hydrogen. The owner can choose to place the electrolyser in proximity to the wind park or in proximity to the industry or site where the hydrogen is to be utilized. While the analysis of which option the owner may choose, based on financial or availability reasons, is not relevant for this chapter, different implications related to the electricity network are shortly discussed below.

If the **hydrogen is produced in proximity to the wind park**, the electricity network is naturally less affected by the installation and the owner can **avoid long lead times related to expanding the electricity network, connection fee, and tariffs**. However, if an electrolyser should be able to supplement the electricity from the wind park **with electricity from the grid, for example to ensure continued production** at times with no or little wind, **the electricity network may nonetheless need to be enhanced**, although that would also **allow electrolysers to operate flexible and supply stability services** to the electrical power system. Furthermore, the owner must then pay a connection fee specifically for the electrolyser, which is not the case if it will run solely on electricity produced by the wind park, and network tariff albeit less than compared to if the electrolyser would run solely on electricity powered from the grid.

For power transmission, the main challenge is the transmission capacity of the grid and the long lead times related to expanding it. Work is underway to investigate if lead times can be shortened and the result of that work is expected to be published in 2023. For hydrogen transmission, similar challenges can be expected, and possibly even more, since many regulations related to a hydrogen system are lacking and, furthermore, most actors (not the least authorities) have very limited experience from handling expansion of a gas transmission grid, and even less for hydrogen. Hence, in addition to proactively developing the regulations, **the lessons that will be learnt regarding processes for expansion of transmission grid and wind power should be applied when developing similar processes for the hydrogen system.**

The transition to fossil-free steel production is, for good reasons, promoted and supported by many actors; including industries, municipalities, politicians at a national (and international) level, and general (and local) public. **The dependance is strong between the hydrogen demand for fossil-free steel and the power supply**, in SE1 mainly from additional wind power, as described here and in the next chapter. However, the social acceptance for new establishments of wind power is not always strong. Would that be improved if the deep connection between the fossil-free steel transition, with all its possibilities, and the need for wind power could be better quantified (e.g. in local jobs and incomes created or emission savings) and communicated?

In the **EU Taxonomy**, which aims to classify sustainable activities for investments, the limit in emissions for production of **"sustainable" hydrogen is set to a 70% reduction** compared to grey hydrogen. Hence, green hydrogen is considered "sustainable" if emissions from electricity are low enough, but also blue hydrogen, despite that blue hydrogen often produces at least three times higher emissions than green hydrogen from the Swedish electricity mix,(IVA, 2022) and hydrogen from biomass can be considered "sustainable".

In the **proposal for revised Renewable Energy Directive**, among other things, **"renewable" hydrogen is defined and the requirements suggested are significantly higher**. Only hydrogen from water electrolysis is considered “renewable”, but not hydrogen from fossil gas, nor from biomass or biogas, and in addition, electricity production must meet strict requirements. **The choice of definition** that will set the limit to be eligible for public support **could have large effects on the development of the hydrogen system** and, hence, would benefit from thorough discussions and investigations, both at national and EU level.

In this prestudy, **several gaps in current legislation with regards to the hydrogen system have been identified**, e.g. as it comes to the need for concession and suitable definitions of hydrogen. Despite the many uncertainties, the interest from industrial actors to develop hydrogen activities is huge. Hence, in order to reduce investment uncertainties and facilitate the desired development, given the potentially large effects on the complete energy system and the transition to fossil-free steel, **a thorough investigation of legislation related to the hydrogen system is recommended**. Such an investigation could include e.g. a Swedish Government Official Report (Statens Offentliga Utredningar, SOU) or, as suggested by Komet,[1] a Government-assigned collaboration, led by a national coordinator, between authorities handling permits related to the hydrogen energy system. Furthermore, as proposed also by the national strategy for electrification,(Infrastrukturdepartementet, 2022) **a national strategy for hydrogen, based on the current proposal,**(Swedish Energy Agency, 2021b) **should be developed**.

However, it should also be considered if **some issues need to be prioritized and investigated in short-term**, e.g. a revision of the Natural Gas Act to include concession and TSO for hydrogen pipelines. Hence, in addition to more thorough investigations, **each actor needs to consider which issues they could improve to facilitate the development of a fossil-free hydrogen system**. For authorities, that could include relatively smaller adjustments to update regulations to consider the recent developments for, or even include at all, hydrogen. For politicians, that could include giving the authorities more clear mandates and deadlines to consider the development of hydrogen in the society, and also to actively provide the Swedish perspective into the EU regulatory development. Industrial **actors are encouraged to continue to take an active role**, and, where appropriate, to a larger extent be allowed to, **in the development of the national and the European regulatory framework**.

[1] Komet lämnar förslag för stärkt förmåga att hantera tillstånd inom vätgasområdet | KOMET (kometinfo.se)

4 Preliminary techno-economic assessments

To reach large-scale hydrogen implementation, an effective and cost-efficient system for storage and transport, strategically designed to connect supply sources to demand centres will be key according to the International Energy Agency (IEA, 2021).

One of the overall project aims was to set the framework for the analysis work required to create a basis for the necessary decisions to obtain a sustainable and cost-effective solution from several different aspects. To accomplish this, increased knowledge and understanding of the most radical systems solutions was deemed necessary. Two scenarios were therefore described and analysed, one in which the region's complete hydrogen demand is assumed to be produced at each industrial sites, and one in which the region's complete hydrogen demand is assumed to be supplied via a hydrogen pipeline.

What is a scenario?

Making accurate and precise long-term prognoses of the future are impossible. A useful approach is therefore to develop scenarios.

Scenarios can help to show possible long-term consequences of decisions made, serve as a basis for discussions and to understand drivers of a certain development.

It is an illustration of what the future may look like, given certain assumptions, and where the interpretation of likelihood is fully up to the viewer.

In this project, the scenarios may be considered as "thought experiments".

This chapter presents preliminary techno-economic analyses of these scenarios, the assumptions made, and the insights concerning the future hydrogen and power markets in terms of demand, supply, and potential infrastructure. This served as the basis for SWOT-analyses, also presented in the report.

Two important cornerstones in the assessment are the future demands as well as the potential production of renewable of power and hydrogen, which are presented in the following.

4.1 Objectives

The objectives of the techno-economic assessments are to:

- Map the future demand of hydrogen and electricity and planned new renewable power production.
- Create two radically different scenarios for production and transmission of hydrogen or electricity.
- Carry out preliminary techno-economic assessments and a SWOT analysis of the two scenarios.

The main aim is to learn about technical and economic characteristics, benefits and drawbacks of the supply systems.

4.2 Scope and definitions

The geographical scope on the Swedish side was set to electricity price area 1 (SE1) and on the Finnish side the Lapland regions and the coastal regions down to Vaasa were considered. This scope constitutes the system boundary of this study.

The energy demand was divided into demands of electrons and molecules (hydrogen separately) and includes all relevant technologies and infrastructures. Electrons and molecules serve as supplementary functions beyond the energy sector. Molecules are for example needed in manufacturing industries, as a significant part of their demand for molecules derives from the need for using them as feedstock.

The definition of electrons and molecules are as follows:

- **Electrons are the energy carrier for electricity -** used for lighting, low-temperature process heat and cooling, smaller-scale operations, and in smaller mobile applications or vehicles, where energy density and range are not as important as in other uses.

- **Molecules include energy carriers in solid, liquid, or gaseous form -** used for higher temperature applications and heating, in larger-scale operations, and larger mobile applications and vehicles, where energy density, range, and off-grid-capability are of essence. Molecules, for example hydrogen, are also needed as feedstocks in the industrial sector.

4.3 Methods

4.3.1 Demand estimations

Statistics of the current energy demand of the considered municipalities were collected from Swedish statistics (Swedish Energy Agency, 2022) and Energiluppen (Energiluppen, 2022). The individually considered municipalities (Luleå, Boden, Gällivare, Kiruna) were selected based on the current knowledge on existing plans for new industrial establishments requiring large supplies of renewable electrons and/or molecules. The demands of the other municipalities were divided into one group for the remaining part of Norrbotten and one group for the three municipalities of Västerbotten included in SE1.

The energy demand was sorted into four different categories: large hydrogen or power consuming industries, other industries, transport, and other sectors (incl. households, service etc), to facilitate demand estimations. Once the demand of electrons and molecules of the four categories was estimated these were summed up for each municipality or group of municipalities. See Appendix 1 for detailed data for each of the municipalities.

The future demands of the large hydrogen or power consuming industries were based on interviews, published plans of establishments and developments, estimations, and assumptions. One preliminary and rough assumption was that 80 percent of the mentioned electricity demand for the large hydrogen users is dedicated for hydrogen production, and that production efficiency of hydrogen in electrolysers is 70 percent.

General assumptions regarding future developments of the population and the vehicle fleet in terms of electrification were made. The population was assumed to increase with 5, 10 and 15 percent for year 2030, 2040 and 2050 respectively, compared to present values. The transport sector was assumed to be electrified to 50 percent in 2030, 75 percent in 2040 and 90 percent in 2050. These figures do not include transport by air or by sea.

4.3.2 Renewable power production

Except taking the existing electricity production (i.e. hydro- and wind power and CHP) into account, only new wind power establishments were considered. Wind power production data were taken from

Vindbrukskollen[1] (2022) as well as the Finnish Wind Power Association[2] (2022). Vindbrukskollen site shows both existing plants and plants permitted, under permission process, and those appealed. The site also shows areas where companies are investigating wind power conditions and so-called areas of national wind power interest.

Wind power projects lacking the estimated annual production was assigned an average factor of 9.6 GWh per year and turbine, based on the projects for which the estimated annual production is available. Additionally, areas suggested for wind power in the municipality plans have also been considered for potential wind power production beyond 2030. Finnish Wind Power Association site also shows existing and permitted plants, as well as projects under evaluation. All projects mentioned in the site are expected to be fully operative by 2030. The annual production is estimated multiplying the installed power taken from the site by an average utilisation factor of 0.35, based on Karjunen et al.(Karjunen et al., 2021) Both in the Swedish and Finnish territory, the estimations of annual wind power production do not consider the obsolescence of older existing turbines.

4.3.3 Visualization

QGIS, an open-source Geographic Information System (GIS), was used to spatially explicit, illustrate the current and future demands as well as the current and potential renewable power production in the region.

4.3.4 Scenario developments

Making accurate and precise long-term prognoses of the future is impossible. A useful approach is therefore to develop different scenarios, that can help us to understand the drivers of a certain development, show possible long-term consequences of events or decisions made and most important, to serve as a basis for discussions. A scenario is an illustration of how the future may look like, given certain assumptions, and where the interpretation of likelihood is fully up to the viewer.

In this prestudy, two completely different hydrogen supply scenarios are investigated. It should be emphasized that these two scenarios should be considered as “radicals”, or “extremes” and that the future reality likely is somewhere in between these. They may be considered as “thought experiments”, where the main purpose is to gain new insights and to learn about the systems characteristics, benefits, and drawbacks.

4.4 Demand of electrons and molecules production

4.4.1 Current demands in Northern Sweden (SE1)

The total energy demand in SE1 in 2020 amounted to almost 39 TWh per year. Molecules constitute the largest share (74 percent, or 29 TWh) of which Luleå needed more than 12 TWh per year. The total SE1 demand of electrons was approximately 10 TWh per year.

4.4.2 Current demands in Northern Finland

Limited data was found on the demands in Finland. Only the current and future demands in the cities of Tornio and Pyhäjoki was considered, using data published by Karjunen et al (Karjunen et al., 2021).

Figure 7 shows the spatial distribution of the energy demands in the region studied.

[1] https://vbk.lansstyrelsen.se/ (lansstyrelsen.se)
[2] https://tuulivoimayhdistys.fi/en/wind-power-in-finland/mapstys

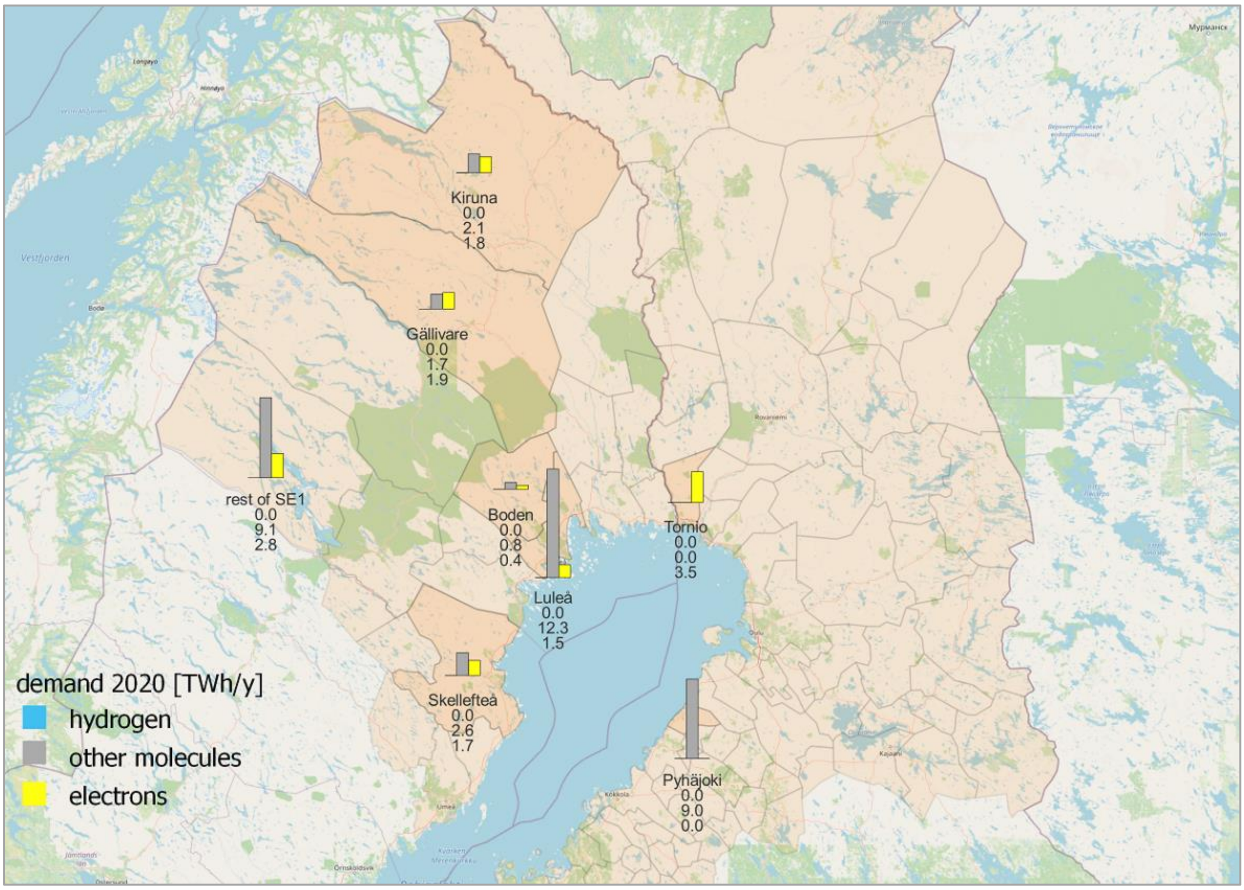

Figure 7. The spatial distribution of the current demands in the studied region

4.4.3 Assessment of the future demands in Northern Sweden (SE1)

A considerable growth in the energy demand is expected due to the industrial establishments planned in the region as illustrated in Figure 8.

Based on company interviews and official reports, the spatial distribution of the molecules and electrons demands for 2030, 2040 and 2050 are shown in Figures 9–11.

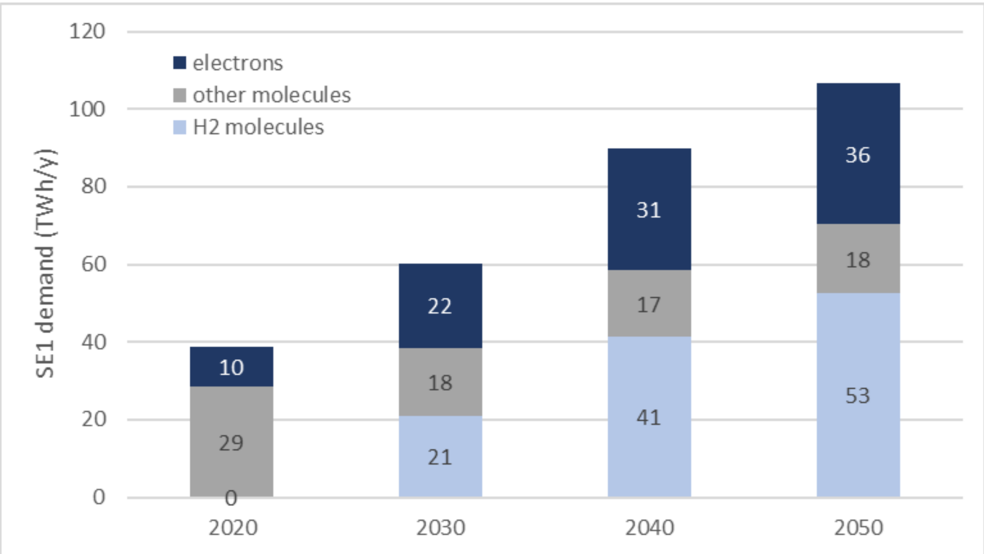

Figure 8. Diagram of the projected demand development, 2020–2050.

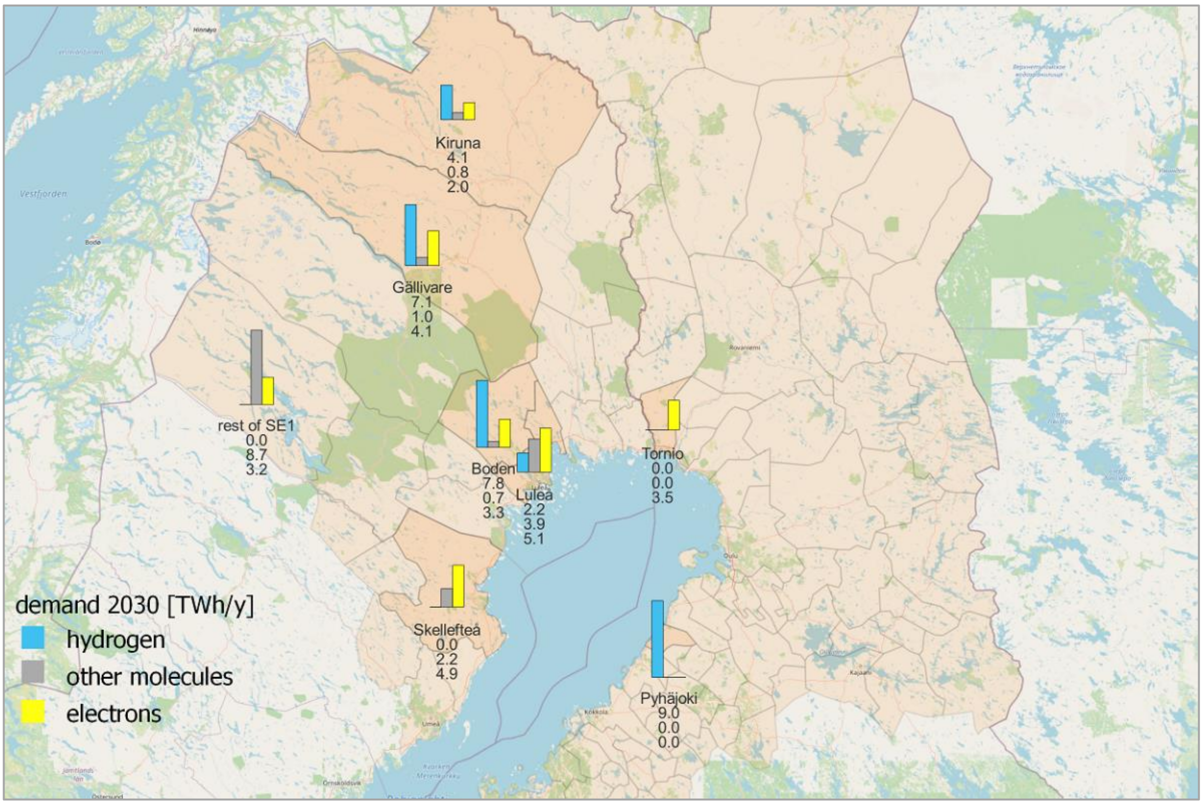

Figure 9. The spatial distribution of the demands 2030 in the region studied.

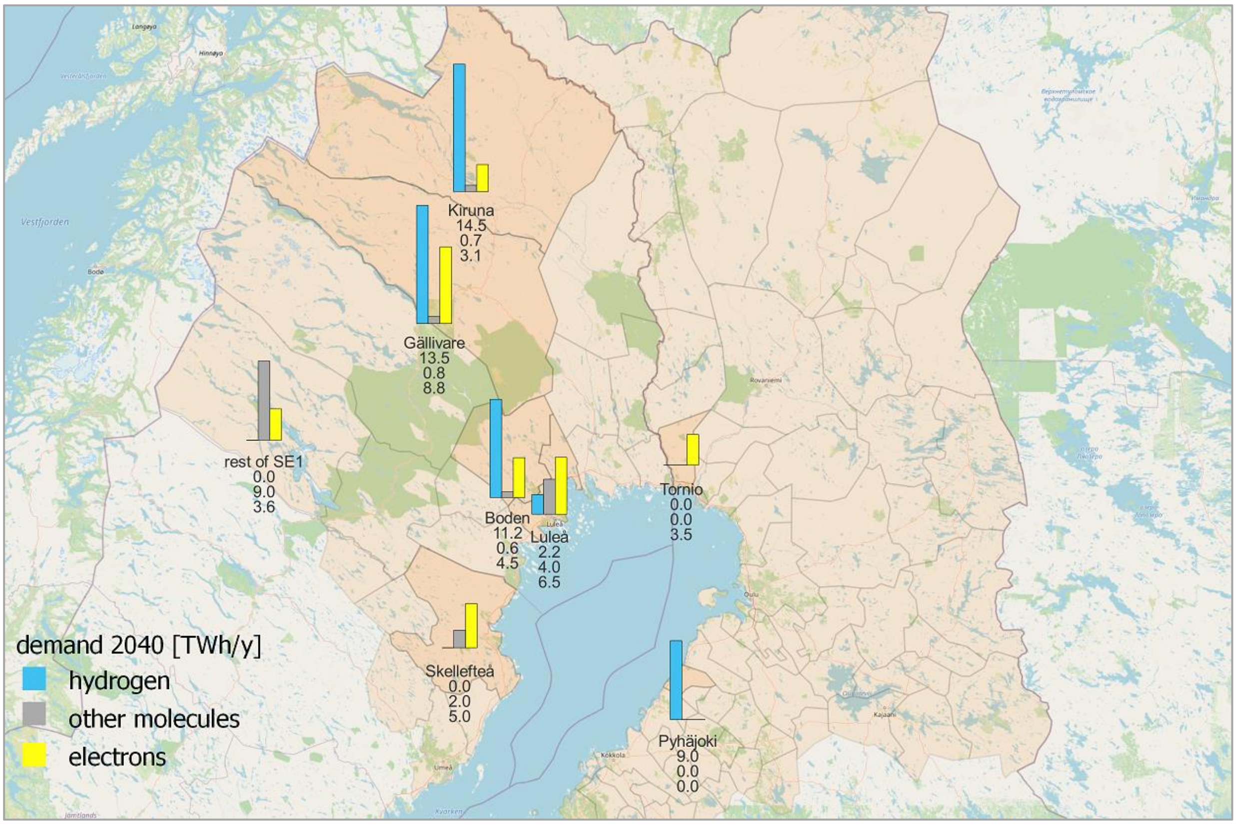

Figure 10. The spatial distribution of the demands 2040 in the region studied.

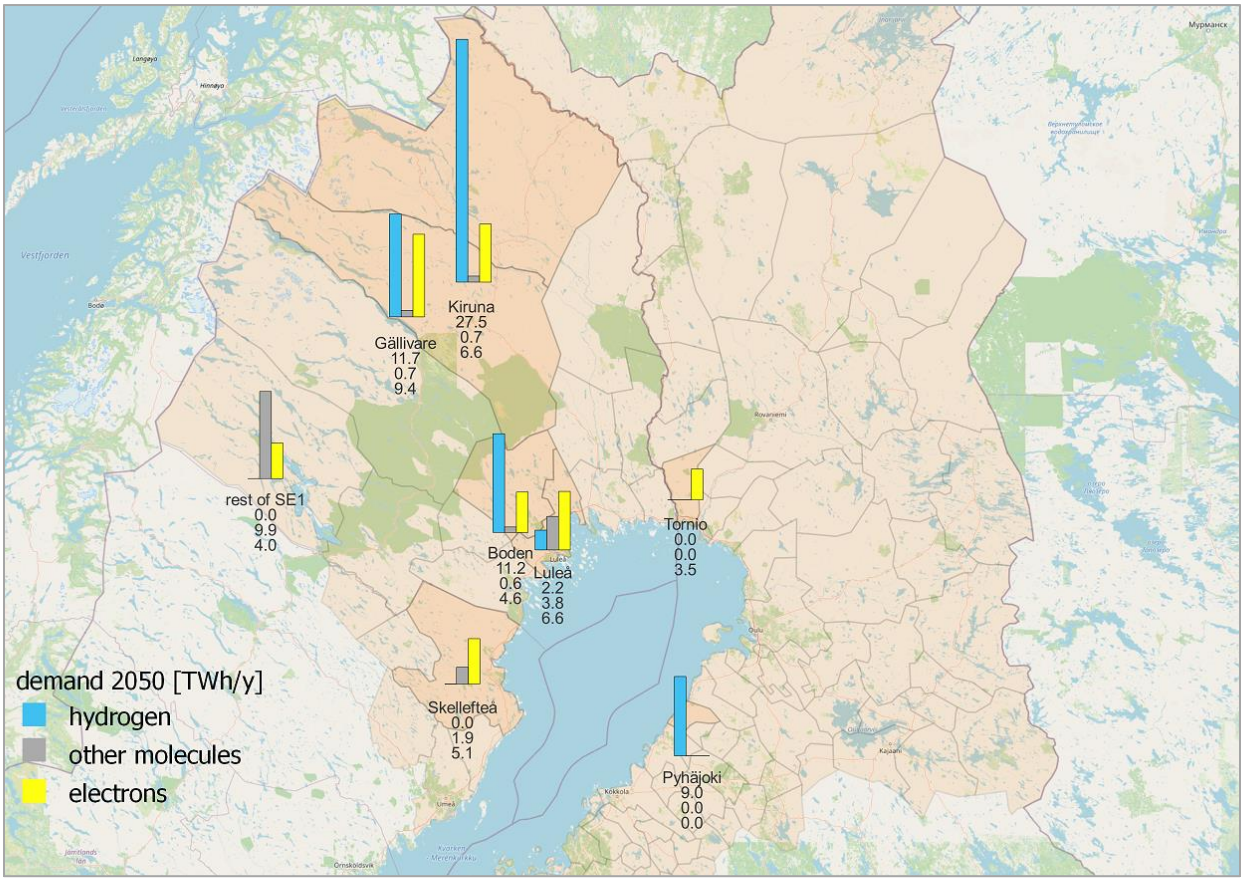

Figure 11. The spatial distribution of the demands 2040 in the region studied.

4.4.4 Estimation of the future production of wind power in the region

Figure 12 shows the geographical distribution of the assessed wind power production in 2030 and 2040, according to the compilation. More detailed numbers are found in Appendix 5.

The total future annual wind power production estimated for 2030 and 2040 in the region is shown in Table 10. It is evident that the studied region on the Finnish side has significantly more extensive plans to build new wind power than in the SE1 area. There is however no data found for how the expansion on the Finnish side may develop after 2030 and is here assumed to be constant until 2050. Karjunen et al. makes a slightly more conservative estimation of wind power on the Finnish side. (Karjunen et al., 2021)

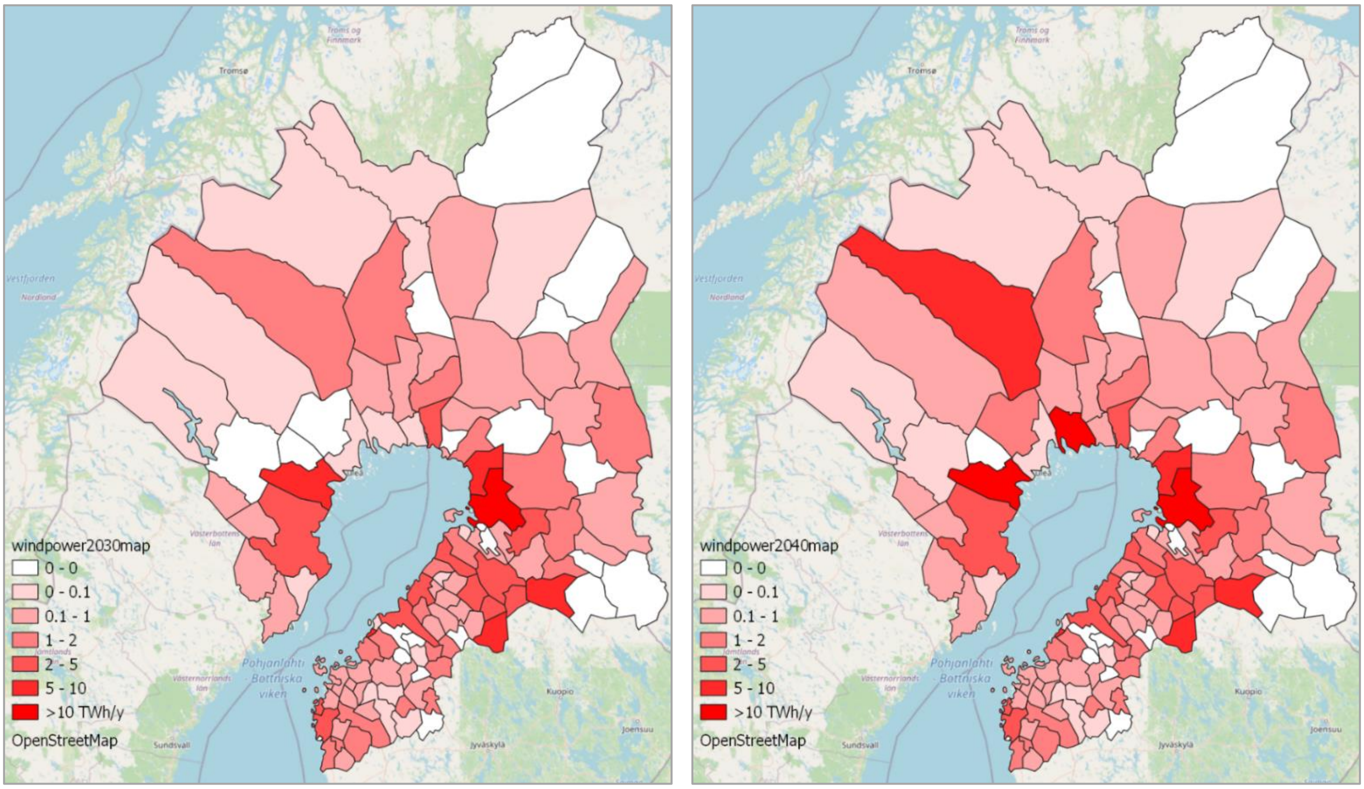

Figure 12. Spatial distribution of planned wind power production in 2030 and 2040, respectively.

Table 10. Estimated total annual wind power production (TWh per year) including present production.

Year	SE1 (Sweden)	Finland
2030	17.4	> 100
2040	> 40	> 100
2050	> 50	> 100

4.5 Scenario A: Power transmission

In this scenario, all hydrogen needed for industrial use is assumed to be produced locally at each of the large demand sites. The hydrogen is generated by electrolysis using renewable power, distributed via new or enhanced power transmission lines, see Figure 13. These local hydrogen islands will also incorporate storages.

The hydrogen demand is assumed to be constant over the year. This in turn means that that intermittent renewable power production must be over-dimensioned along with electrolyser and storage capacities, sufficiently dimensioned to be able to utilise intermittent power production when available. There are several trade-offs in between the power production, electrolyser and storage capacity, and which combination thereof that are realised comes down to preferences of overall system operability, economics, interlinkages, and development of other parts of the energy's system, robustness etc as well as a multitude of system external factors.

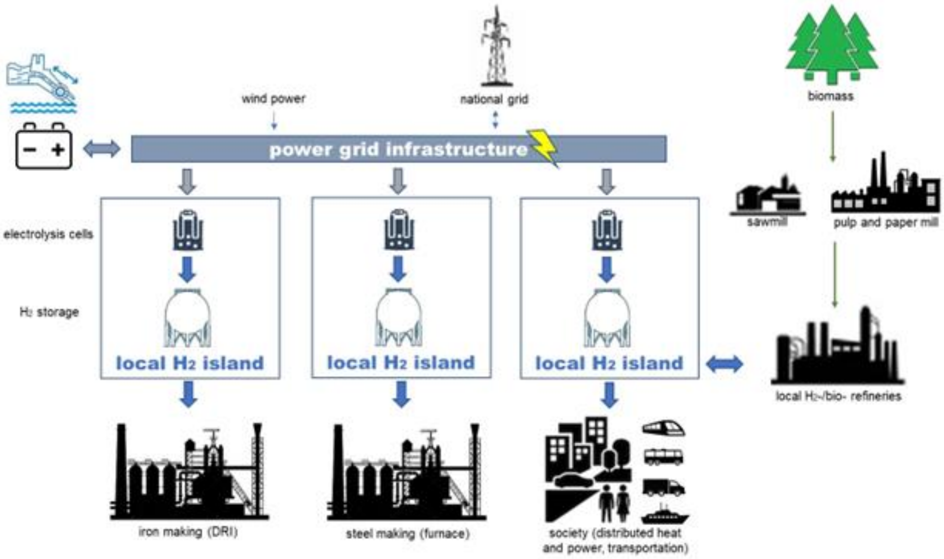

Figure 13. Basic system description for Scenario A.

In this scenario, it is assumed that both hydrogen demand and electricity demand are supplied by existing power generation (2021) and planned renewable (mainly wind) power generation (2030, 2040 & 2050) based on the assessments made in SvK LMA2021, see Table 11.

Table 11. Annual power balance (TWh per year) for the years 2030-2050

	2030	2040	2050	
Power demand[1]	53	91	112	TWh per year
Current production in SE1	27	27	27	TWh per year
Planned additional power production[2]	13	21-36	32-57	TWh per year
Deficit	13	28- 43	28-53	TWh per year

The power balance shows that the present electricity production is not sufficient to fulfill the estimated demand. Adding the planned new power production in SE1 will also not be enough. This means that electricity imports to SE 1 are required ranging from 13 TWh per year in 2030 to up to 50 TWh in 2050.

The current maximum transmission capacity from Norway to SE1 is 700 MW, and from Finland to SE1 1100 MW (Svenska Kraftnät, 2021a). With an optimistic assumption that the transmission corridor is running at 80 % capacity for the whole year, the maximum amount of electricity that can be imported from Norway and Finland is 4.9 TWh per year and 7.7 TWh per year, respectively. This sums up to 12.6 TWh per year, which is not enough to compensate for the assessed power deficits in SE 1. Electricity import from Norway and Finland is not always the case during the whole year. The

[1] Demand is calculated by the sum of electricity demand for other purposes plus the demand for H2-production assuming a 70% electrolyser efficiency, see Appendix 1 for details.
[2] According to SvK LMA2021. Lower is *Scenario Elektrifiering planerbart*, higher is *Scenario Elektrifiering förnybart.*

capacity is planned to be increased to 2000 MW by 2026 by the addition of the Aurora-line.(Svenska Kraftnät, 2021b)

The transmission corridor from SE2 to SE1 has a maximum capacity of 3300 MW. The maximum amount of electricity (optimistic situation) that can be transmitted from SE2 to SE1 will be around 23 TWh per year. With the most optimistic assumption that Norway, Finland, and SE2 almost all fully use the transmission lines to export electricity to SE1, the maximum electricity imported to SE1 could be summed up to 36.6 TWh per year (most optimistic situation). Power flow, in reality, is governed by a multitude of factors, willingness to pay for electricity being a major one, in addition to technical potential. The maximum import capacity still falls short of the higher ranges of the projected deficits in SE1 for 2040 and onwards.

Considering that planned new renewable power generation in Finland is exceeding 100 TWh per year already in 2030, the most feasible option is likely to build new transmission corridors between Sweden and Finland to cover the deficit in SE1 in the years to come.

Transmission losses has not specifically been accounted for in this assessment, in 2015 these accounted for 2.8% of the power feed into the high voltage distribution grid in Sweden (Helander, 2017). So, even though losses are not negligible, the shorter transmissions distances considered within this study, and given the overall uncertainty in the other parameters, loses does not warrant a detailed assessment at this stage.

4.5.1 Scenario for strengthened power transmission infrastructure

The strengthening of the power transmission grid in SE1 may take place in stages, gradually increasing the capacity in three steps. After discussions with relevant actors and stakeholders it is likely that a version of stage 1 will be constructed. Stages 2 and 3 are however dependent on a possible development of a pipeline system for hydrogen distribution.

Stage 1 is focusing on the proposal for coming offshore wind power connection in the Bothnian Bay (Svenska Kraftnät, 2022a). This will have a transmission capacity of 1.4 GW and is most likely connected to nearby Luleå and Boden. In the same stage, a reinforcement along Lule River is proposed to transmit electrical power north to Gällivare, Svappavaara and Kiruna. As the power supply to the industrial sites is crucial, it is also important to have redundant power lines. Therefore, new lines directly from hydropower stations in Lule River to Kiruna are required. Stage 1 will provide a capacity of 3.8 GW to Kiruna with redundant supply routes. A plausible layout is shown in Figure 14. It can be running at full capacity by about 2035.

Figure 14. Stage 1 in the power transmission scenario will provide a capacity of 3.8 GW to Kiruna with redundant supply routes. The offshore wind in the Bothnian Bay will have a capacity of 1.4 GW.

The total distance of the power lines is summarized to 721 km. The cost per km depends on the capacity of the line and is estimated to stretch between 1 and 2.3 M€. However, the offshore connection is probably more expensive and estimated to 4.8 M€/km. The total cost of stage 1 is then summarized to 1,392 M€ as shown in Table 12.

Table 12. Estimated distances and cost for the stage 1 in the power transmission scenario.

From	To	Distance (km)	Capacity (MW)	Capacity (TWh/year)[1]	Cost per km (M€)	Cost (M€)
Bottenviken havsbas	Boden	90	1400	10	4.8	429
Kukkolaforsen	Töre	76	500	4	1.0	72
Töre	Boden	63	500	4	1.0	60
Boden	Porsi	50	2800	20	2.3	114
Porsi	Harsprånget	50	2800	20	2.3	114
Harsprånget	Gällivare	50	2800	20	2.3	114
Gällivare	Svappavaara	75	2800	20	2.3	171
Svappavaara	Kiruna	47	2800	20	2.3	107
Vietas	Kiruna	100	500	4	1.0	95
Porjus	Kiruna	120	500	4	1.0	114
Total		**721**				**1392**

Stage 2 is focusing on the expected additional wind power in northern Finland. Stage 2 is adding a capacity of 2.8 GW via a direct additional transition line from Finland through Vitsaniemi, Svartbyn, Porsi and Gällivare. A plausible layout is shown in Figure 15 and provide additional redundancy to both Gällivare and Kiruna. It can be up running in full capacity by earliest 2040.

The total capacity to Kiruna after completion of stage 2 is 6.6 GW. The distance of the stage 2 power lines is summarized to 388 km. The cost per km is, same as before, estimated to 2.3 M€. The total cost of stage 2 is then summarized to 887 M€ as shown in Table 13.

Table 13. Estimated distances, capacity, and cost for the stage 2 in the power transmission scenario.

From	To	Distance (km)	Capacity (MW)	Capacity (TWh/year)[2]	Cost per km (M€)	Cost (M€)
Vitsaniemi	Svartbyn	43	2800	20	2.3	98
Svartbyn	Porsi	130	2800	20	2.3	297
Porsi	Gällivare	100	2800	20	2.3	229
Gällivare	Kiruna	115	2800	20	2.3	263
Total		**388**				**887**

Stage 3 is focusing on the potential additional wind power production in both northern Sweden and Finland. Stage 3 is adding a capacity of 2.8 GW via a direct additional transition line from Finland

[1] With an optimistic assumption that the transmission corridor is running at 80 % capacity for the whole year
[2] With an optimistic assumption that the transmission corridor is running at 80 % capacity for the whole year

through Pajala and Svappavara. Further the existing line between Porjus and Kiruna is strengthened with additional 1.4 GW. A plausible layout is shown in Figure 16 and provide additional redundancy to Svappavara. It can be up running in full capacity by earliest 2045.

Figure 15. Stage 2 in the power transmission scenario will provide an additional capacity of 2.8 MW summarizing to total capacity of 6.6 GW to Kiruna with redundant supply routes. The additional power is assumed to transfer a significant quantity of Finnish wind power.

Figure 16. Stage 3 in the power transmission scenario will provide an additional capacity of 4.2 MW summarizing to total capacity of 10.8 GW to Kiruna with redundant supply routes. The additional power is assumed to transfer a significant quantity of Finnish wind power in the very north, through Pajala.

The total capacity to Kiruna after completion of stage 3 is 10.8 GW. The total distance of the stage 3 power lines is summarized to 312 km. The total cost of stage 3 is then summarized to 576 M€ as shown in Table 14.

Table 14. Estimated distances, capacity, and cost for the stage 3 in the power transmission scenario.

From	To	Distance (km)	Capacity (MW)	Capacity (TWh/year)[1]	Cost per km (M€)	Cost (M€)
Harsprånget	Porjus	10	2800	20	2.3	23
Porjus	Kiruna	120	1400	10	1.1	137
Pajala	Svappavaara	135	2800	20	2.3	309
Svappavaara	Kiruna	47	2800	20	2.3	107
Total		**312**				**576**

The combined costs for the fully built system, incorporating all three stages, equates to 2855 M€. Given the assumptions in Table 15, this yields a cost of slightly above 0.12 €/kgH2, out of which 0.11 €/kgH2 makes up the CAPEX, the remainder being the operating expenditures.

Table 15. Assumptions made regarding the transmission grid

CAPEX of fully build transmission grid	2855 M€
O&M of transmission lines	1% of CAPEX (AEMO, 2021)
Lifetime	40 years
Discount rate	5%

Large transmissions lines have an impact on the landscape and the wildlife therein. The impact is often considered particularly disruptive when placed in new terrain.[2] Apart from the purely aesthetic impact there can also be effects on bird and other animals' migration, edge effects and habitat fragmentation, changes in vegetation etc.

Some of these effects can be mitigated by carefully selecting the route, timing construction properly throughout the year etc. Environmental, ecological, and aesthetic impacts have not been considered in this study, but they will have to be. This might add to the projected costs of the power lines.

4.5.2 Proposed electrolyser and storage installations

The production cost of hydrogen from water electrolysis depends mainly on the CAPEX of the electrolysers and the costs for the required electricity. The dimensioning of the electrolysers at each usage node depends on a multitude of factors, hydrogen demand being the foremost of these naturally. Furthermore, the number of operation hours of the electolysers is a balance where high capacity factors reduce the CAPEX per kg hydrogen, while lower capacity factors could provide flexibility to avoid operation during hours with high electricity prices.

Future electricity prices are challenging to estimate and subject to many uncertainties. Nonetheless, SvK has used extensive modelling of several scenarios, to provide understanding of possible future developments and electricity prices for the Swedish energy system, in their long-term market analysis

[1] With an optimistic assumption that the transmission corridor is running at 80 % capacity for the whole year
[2] Mitigating the environmental impacts of transmission lines - Fingrid

from 2021 (LMA2021).(Svenska Kraftnät, 2021a) Most interestingly, they have put extra efforts into the mutual dependence between the electricity and the hydrogen system. In their scenario Elektrifiering Förnyelsebart (EF, Electrification Renewables), assuming that all new plants provide renewable power and that current nuclear plants are decommissioned before 2045, a hydrogen demand for the steel industry in SE1 of ca. 65 TWh_{el} with hydrogen storage for 7 days (and additional ca. 20 TWh_{el} for electrofuels). Hence, the demand is similar, although not identical, to what is found in this project for 2050 (ca. 52 TWh_{H2} require ca. 75 TWh_{el}) and, thus, the LMA2021 may provide a reasonable estimate for the electricity prices in 2050 for electrolysers connected to the grid in SE1.

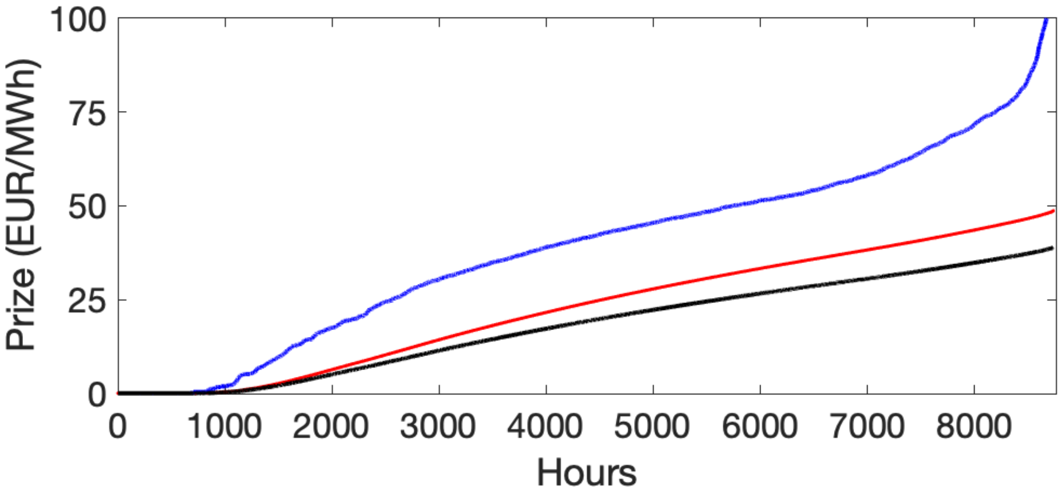

Figure 17. Price-duration curves based on spot prices (blue) from LMA2021 (Svenska Kraftnät, 2021a) *and the average spot prices (black) and prices for grid-connected electrolysers (red) up to a certain hour.*

The data (which has been kindly provided in raw-format to RISE by SvK) from LMA2021 scenario EF for 2045 provide a price-duration curve for spot prices in SE1 (blue curve in Figure 17). For each hour, the average of all lower spot prices (black curve), scaled to include costs corresponding to 25% of spot prices for grid connection (DNV, 2022) (red curve), provides an estimate of the average electricity price for an electrolyser that operate for that number of hours, with flexibility to operate only during the hours with lowest prices. For an electrolyser operating according to the conditions given in LMA2021, i.e. for 4380 h per year, the average electricity price is then ca. 24 EUR/MWh.

The cost of electrolysers is expected to be reduced significantly over the next decades due to scaling effects related to both larger systems and increased production rates. The electrolyser cost has been projected to fall from ca. 700 EUR/kW for a 100 MW system in 2020 to ca. 500 EUR/kW by 2030, (Fraunhofer Institute, 2021) and further to 130-307 EUR/kW in 2050.(IRENA, 2020) Also, their life-time is expected to increase from ca. 10 years to 20 years by 2050 (IRENA, 2020). Here, we assume a cost for an electrolyser system in 2040 to be 400 EUR/kW with a life-time of 15 years.

As stated above, the costs for grid connection for the electrolysers are assumed to be 25% of the spot prices (DNV, 2022).

Table 16. Assumptions for the calculations regarding electrolysers.

CAPEX of electrolysers	400 EUR/kWe	In between (Fraunhofer Institute, 2021; IRENA, 2020)
O&M of electrolysers	3% of CAPEX	(Reuß et al., 2017)
Electricity consumption	47.6 kWh_e/kg H2	corresponds to a 70% efficiency of the electrolysers (Reuß et al., 2017)
Electricity cost	13-35 EUR/MWh	These prices are the minimum and maximum (with 24 EUR/MWh as mean), for the annual averages of electricity prices for the 35 different weather years modelled in LMA2021 EF for 2045 (Svenska Kraftnät, 2021a) This includes the costs for grid-connection which are assumed to be 25% of spot prices (DNV, 2022).
Annual operation hours	4,380 h	
Lifetime	15 years	The average lifetime given in (Fraunhofer Institute, 2021; IRENA, 2020)
Discount rate	5%	

Table 17. Assumptions for the calculations regarding hydrogen storage

CAPEX of lined rock cavern	55.4 EUR/kgH2	With max pressure 250 bar (Papadias & Ahluwalia, 2021)
O&M of lined rock cavern	2% of CAPEX	(Reuß et al., 2017)
Storage capacity	7 days	Storage at each node, to last for 7 days at average annual consumption.
Lifetime	30 years	(Reuß et al., 2017)
Discount rate	5%	

In this scenario it is assumed that the hydrogen storage be build large enough to supply the demand at each node for 7 days. This provides some flexibility in the operation of the electrolyser, in addition to maintenance etc. Dimensioning the electrolysers and storage this way however somewhat limits the potential to fully utilise the more fluctuating electricity prices that comes with a power supply with a larger share of intermittent power production, such as wind. Table 18 shows the industrial hydrogen demand development.

Table 18. Industrial hydrogen demand in SE1 (TWh per year)

	2030	2040	2050
Kiruna	4.1	14.5	27.5
Gällivare	7.2	13.5	11.7
Boden	7.8	11.2	11.2
Luleå	2.2	2.2	2.2
Total	*21.3*	*41.2*	*52.6*

The model in LMA2021 includes flexible production in the existing hydropower facilities. However, the demand flexibility provided by hydrogen production and storage significantly reduce the annual number of hours with loss of load expectation (LOLE, i.e. lack of power due to too low production and imports), in scenario EF for 2045 from 889 to 40 h (which is further reduced to 0.5 h when demand flexibilities from electric vehicles and server halls are also included). (Svenska Kraftnät, 2021a) Hence, the possibility to operate electrolysers connected to the grid flexible not only could enable reduced costs for hydrogen, but also improve the stability of the electricity system for a scenario with very high penetration of variable renewable power production.

The required electrolyser capacities given 4,380 annual operating hours are shown in Table 19, and the needed hydrogen storage capacities are shown in Table 20.

Table 19. Required electrolyser capacities (GW).

	2030	2040	2050
Kiruna	1.3	4.7	9
Gällivare	2.3	4.4	3.8
Boden	2.6	3.7	3.7
Luleå	0.7	0.7	0.7
Total	*6.9*	*13.5*	*17.2*

Table 20. Needed hydrogen storage capacities (kton).

	2030	2040	2050
Kiruna	2.3	8.3	15.7
Gällivare	4.1	7.7	6.6
Boden	4.5	6.4	6.4
Luleå	1.3	1.3	1.3
Total	*12.1*	*23.7*	*30*

Table 21. Capacity and CAPEX for local electrolytic hydrogen production and storage in year 2050. The numbers are based on the costs of 400 EUR/kWe for electrolyser and 55.4 EUR/kg H2 for storage.

	Boden	Gällivare	Kiruna	Luleå	*Total*
Electrolyser capacity (MW)	3700	3800	9000	730	17200
CAPEX electrolyser (MEUR)	1460	1520	3600	290	6900
Storage capacity (tonnes)	6400	6600	15700	1300	30000
CAPEX storage (MEUR)	350	370	870	70	1660

The production cost for hydrogen, which is highly dependent on the electricity costs, range from 1.4 to 2.5 €/kgH_2 for the simulated weather year with the lowest electricity price to the one with the highest. The average electricity price for all modeled weather years in LMA2021 scenario *Elektrifiering Förnyelsebart* with an annual operation of the electrolysers of 4,380h is 24 €/MWh. This gives a hydrogen price of 2 €/kg H_2, see Figure 18.

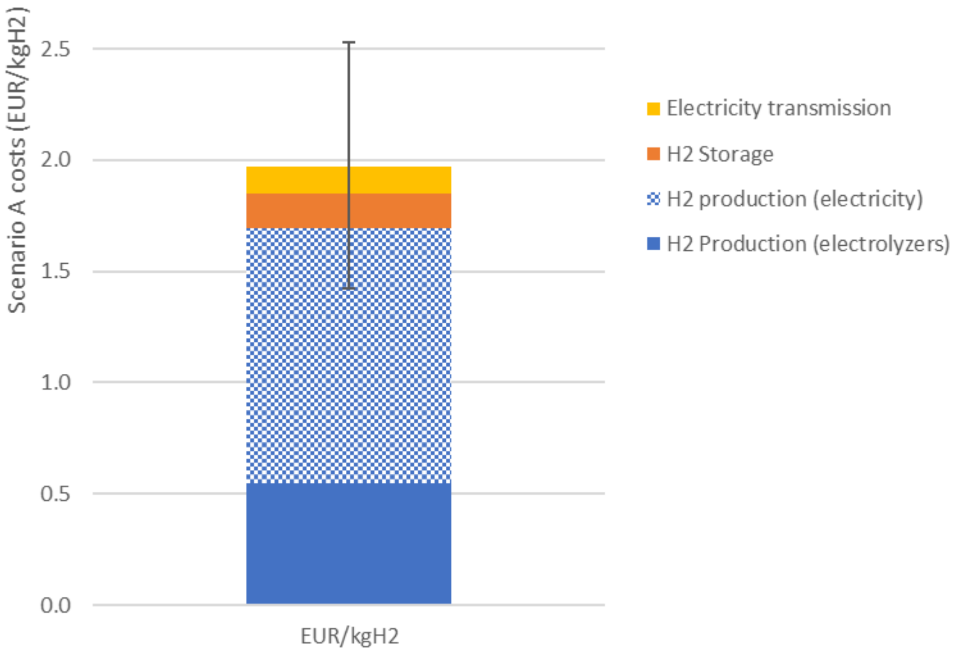

Figure 18 Total specific infrastructure cost for Scenario A.[1]

The electrolyser CAPEX is 0.42 €/kgH_2 and the OPEX (electricity cost and O&M) 0.9 to 1.8 €/kgH_2. For the storage, the corresponding numbers are 0.08 €/kgH_2 and 0.09 €/kgH_2, respectively. For the power transmission, the CAPEX is 0.11 €/kgH_2 and the OPEX 0.02 €/kgH_2.

4.6 Scenario B: Hydrogen transmission

At present, approximately 5 000 km of hydrogen pipelines are currently in operation, to a large extent located in Europe and the United States (90%). Most of them are closed systems owned by large merchant hydrogen producers concentrated near industrial consumers, mainly refineries and chemical

[1] Cost of electrolyser grid connection included in electricity price, 25% of spot price (DNV, 2022).

plants. Attaining hydrogen strategy targets will require a fast hydrogen transmission development. IEA Net Zero Emissions by 2050 Scenario analysis shows that by 2030, the total length of hydrogen pipelines globally will need to quadruple to >20 000 km (IEA, 2021).

In this scenario, the hydrogen is assumed to be transmitted to the industrial users via pipelines only. The hydrogen is produced via electrolysis based on grid-independent renewable wind power. Central, large-scale electrolysis units are placed in the vicinity of the pipeline or close to the power production depending on assumed conditions. Potentials for utilisation of residual heat and oxygen are also considered when the location was chosen.

4.6.1 Preliminary considerations

The layout of the pipeline infrastructure will be functional to its main purpose, i.e., to transport the green hydrogen produced with the power generated by wind farms (mainly on the Finnish coastline) to the demand sites (mainly in the Swedish Lapland). To minimize overall length, the pipeline will follow the coast and will depart from it on the Norrbotten side to reach the demand sites in Gällivare and Kiruna (loosely along the road/railway from Luleå/Boden). Spatially, it seems convenient to have the T-junction in Boden rather than elsewhere (e.g., if the pipeline followed the coast directly to Luleå, an almost parallel segment would be necessary to reach Boden from Luleå).

Main stations along the pipeline have been identified according to two criteria: 1) locations of demand sites and 2) locations where electrolyzing facilities can be installed concentrating the renewable power generated by the wind farms in the surroundings (about a 100 km radius, preferring locations where the waste heat can be exploited by district heating systems). Stations with electrolyzing facilities will be coupled to adequate storage facilities to deal with the intermittency of wind power. Some of the stations, at an adequate distance from one another, will also provide recompression to overcome the pressure losses in the pipes.

Based on the data collected about wind power generation and hydrogen demand sites, the identified stations are: Kokkola, Pyhäjoki, Oulu, Tornio, Boden, Gällivare, Kiruna, Luleå, and Skellefteå. The initial layout of the pipeline infrastructure connecting all the stations is shown in Figure 19.

4.6.2 Mass balances

The mass flow rates of hydrogen to be transmitted by each segment of the pipeline connecting two main stations are calculated by considering the demand at each station and the local production of hydrogen by the electrolyzing facilities. A local deficit must be supplied by hydrogen taken from the pipeline, while a local surplus can be made available for other stations through the pipeline.

The hydrogen demand at the stations is taken from Appendix 1 and are summarized in Table 22.

Table 22. Industrial hydrogen demand within the system boundary (TWh per year)

	2030	2040	2050
Kiruna	4.1	14.5	27.5
Gällivare	7.2	13.5	11.7
Boden	7.5	11.2	11.2
Luleå	2.2	2.2	2.2
Skellefteå	0.5	0.5	0.5
Pyhäjoki	9.0	9.0	9.0

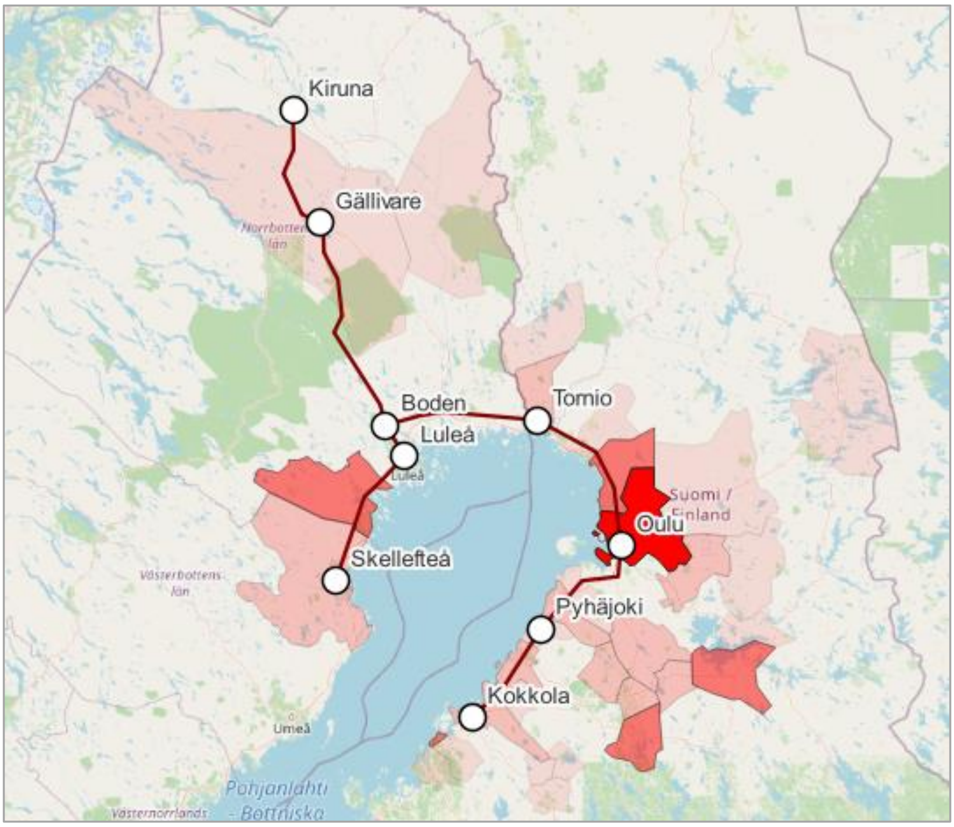

Figure 19. The initial layout of the pipeline infrastructure connecting all the stations.

Local hydrogen production is calculated considering the generated wind power that can be concentrated at the station from a radius of approximately 100 km and then a conversion factor up to 0.7 as shown in Table 23.

Table 23. Nearby wind power and local hydrogen production (TWh per year).

Nearby wind power [TWh/y]				Local H_2 production [TWh/y]			
	2030	2040	2050		2030	2040	2050
Gällivare	2.5	7.4	7.4	Gällivare	1.7	5	5
Boden*	9.6	26.4	26.4	Boden*	6	18.4	18.4
Tornio	9	9	9	Tornio	6	6	6
Oulu	30	30	30	Oulu	21	21	21
Pyhäjoki	26.3	26.3	26.3	Pyhäjoki	18	18	18
Kokkola	25	25	25	Kokkola	17	17	17

**wind power from most SE1 coastal municipalities is concentrated to around Boden*

Accordingly, the hydrogen energy flow to be transported in each segment of the pipeline is shown in Table 24.

Table 24. Transported hydrogen (TWh per year)

Transported hydrogen [TWh/y]			
(From-To)	2030	2040	2050
Gällivare-Kiruna	4.05	14.52	27.53
Boden-Gällivare	9.5	23	34.2
Torneå-Boden	13.72	18.54	29.74
Oulu-Torneå	7.72	12.54	23.74
Pyhäjoki-Oulu	0	0	2.74
Kokkola-Pyhäjoki	0	0	0
Boden-Luleå/Skellefteå	2.74	2.74	2.74

The results shows that approximately 14 TWh per year of hydrogen will be produced in and imported from Finland in the year 2030 corresponding to around 20 TWh per year of renewable power with assumed electrolyser efficiency. This power demand corresponds to less than 20% of the new planned wind power production in Finland (115 TWh per year). The hydrogen imports are likely to increase with time and in 2050, we estimate that close to 30 TWh per year will cross the border. With the same efficiency assumption this equals 43 TWh per year of renewable power and still well below the planned capacity in Finland.

About the layout of the infrastructure, some segments of the pipeline (from Kokkola to Oulu) will not be strictly needed until 2050, the Pyhäjoki steel mill just relying on the local hydrogen production. The hydrogen demand in Skellefteå is also marginal compared to that of the other sites and probably could be satisfied locally. Hence, the part of the infrastructure that is essential to be completed by 2030 is the one shown in Figure 20.

A recompression facility is added to the station in Boden as it divides the path from Oulu to Kiruna into two traits of approximately the same length (around 250 km). It is envisaged that a second recompression facility will be added in Oulu when the pipeline segments from Kokkola to Oulu will be built by 2050 (another path of around 250 km).

4.6.3 Size of pipeline segments

Although some segments of the pipeline are even not present in temporary 2030 layout, the sizing of the segments must take the highest hydrogen mass flow rates into account anyway, i.e., those in 2050. These mass flow rates are rounded up to 35 TWh per year (Boden to Gällivare, 33.3 kg/s), 30 TWh per year (Gällivare to Kiruna and Tornio to Boden, 28.5 kg/s) and 25 TWh per year (Oulu to Tornio, 23.8 kg/s).

The diameter of a pipe suitable for the transmission of a given hydrogen mass flow rate mainly depends on three factors:

1. The inlet operating pressure, i.e., the nominal maximum pressure of the pipeline that results from the compression of the gas at the beginning of the pipeline and is restored by the recompression facilities along the way.
2. The lowest (or minimum) operating pressure allowed in the pipeline before recompression is needed.
3. The gas velocity inside the pipeline. Please note that, in a rigorous hydraulic model of the pipes, the minimum operating pressure and gas velocity are actually linked by two other quantities: the actual length of the pipe and the friction factor (because the difference between

maximum and minimum operating pressure is equal to the pressure losses in the pipe due to wall friction, which depend on pipe length and gas velocity).

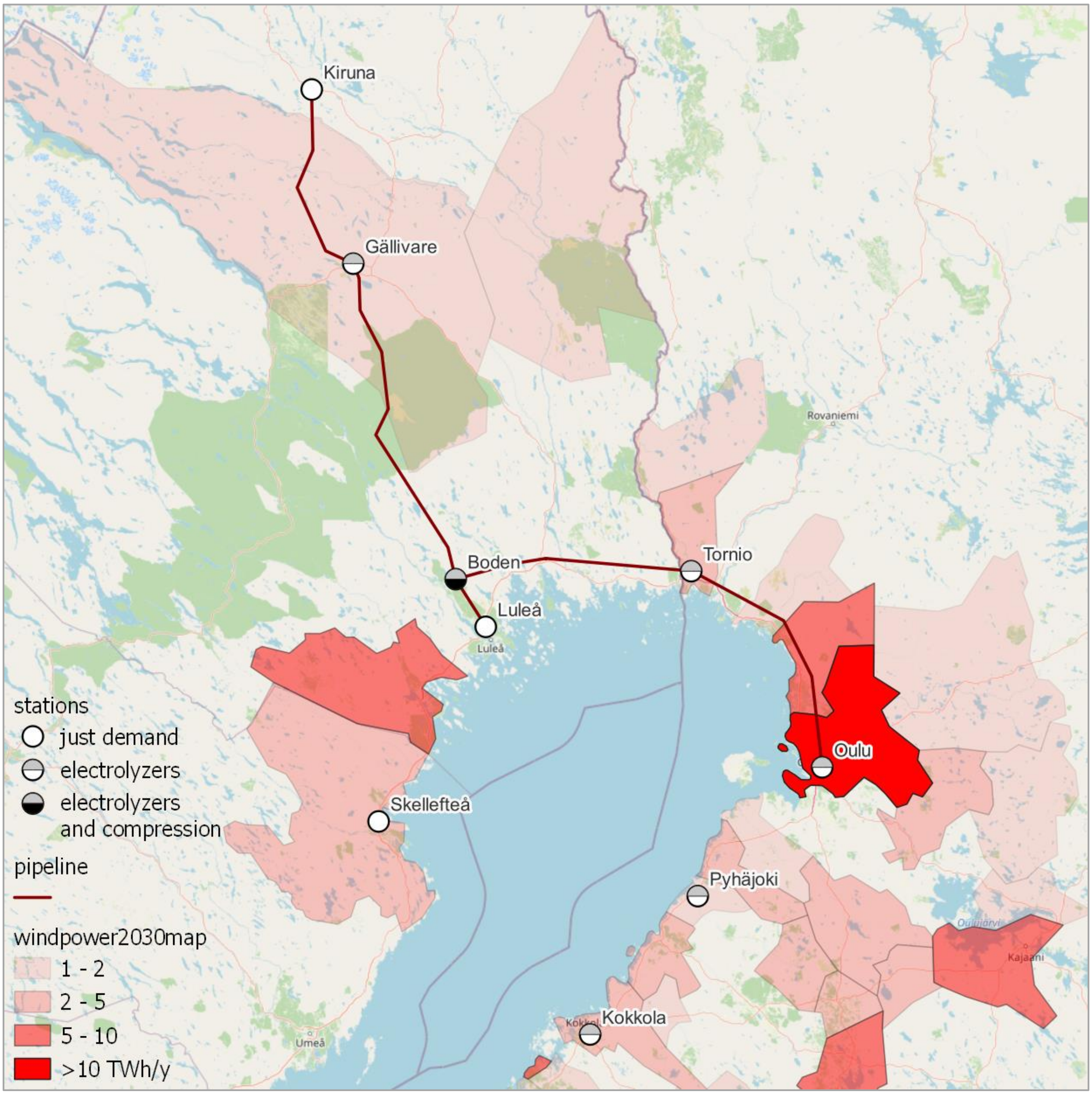

Figure 20. Infrastructure that is essential to be completed by 2030.

Assuming that the pipeline will be underground (for constant operating temperature etc, see below), the following diameters can be calculated with simplified hypothesis on average gas flow conditions in the pipes:

- Flow temperature = 283 K
- Average pressure = 90 bar (max 100, min 80)
- Average density = 7.394 kg/m^3
- Average velocity = 12.1 m/s

Table 25 shows the resulting mass flows and pipeline diameters for different capacities.

Table 25. Resulting mass flows and pipeline diameters

Pipe capacity	[TWh/y]	25	30	35
Pipe capacity	[MW]	2854	3425	3995
H_2 mass flow	[kg/s]	23.8	28.5	33.3
Section	[m^2]	0.27	0.32	0.37
Diameter	[m]	0.58	0.64	0.69

The more accurate hydraulic model of the pipes (assuming a fixed length of 250 km) confirms this result. The same model shows that the diameter of the 35 TWh per year pipe would be 0.85 m for maximum and minimum operating pressures of 70 and 60 bars, respectively, and an average gas velocity of 11.2 m/s. Both estimations are well below the maximum pipe diameter considered in the literature (48 inches), (European Hydrogen Backbone, 2022a) meaning that no segment of the pipeline is likely to need pipe sections in parallel to transport the required hydrogen mass flow rates.

Please note that the choices about maximum and minimum operating pressures and gas velocity affect the capital and operational costs of the infrastructure. In fact, larger pipe diameters (which result from lower maximum pressures, lower allowed pressure losses and lower gas velocities) increase the capex of the pipes but reduce the CAPEX and the OPEX of the compression and recompression facilities.

4.6.4 Land use and landscape changes

As mentioned, it is assumed that the pipelines will be put underground, due to safety reasons and others,(Walker et al., 2018) but also to keep the temperature constant. It is furthermore likely that an uninhabited area safety zone will be required. Walker et al. claim that in the order of 20 m width will be needed, but this depends on depth, pressure, and diameter.(Walker et al., 2018) Agricultural cultivations above the pipeline seems to be possible.

4.6.5 Preliminary cost estimations

This preliminary estimation of the cost is performed considering the segments of the pipeline connecting Oulu, Tornio, Boden, Gällivare and Kiruna, and the facilities present at these stations. No segments/stations are considered south of Boden or Oulu since those pipes will probably be sized according to strategic decisions about the transmission capacities from (or even to) the southern regions of Sweden and Finland.

All costs per kg or MWh of hydrogen use the total amount of hydrogen to be delivered by the infrastructure to the final users in SE1 in 2050 (52.6 TWh per y) as reference.

The costs of the infrastructure are calculated for:

- Electrolyzing facilities for hydrogen production
- Lined rock caverns for hydrogen storage (including the compression from electrolyzing facilities output)
- Pipes and recompression stations for hydrogen transmission

using assessed hydrogen demands, local productions and transmitted mass flow rates in the year 2050.

Two methods from two different sources are used to estimate the costs for hydrogen transmission and in the following they will be referred to as Method 1 (European Hydrogen Backbone, 2022a) and Method 2.(Walker et al., 2018)

In Figure 21, all costs of the infrastructure using both methods are summarized for Scenario B. It is apparent that the specific transmissions costs, no matter which method used to evaluate them, are marginal compared to those for production and, to a lesser extent, storage costs. The total specific cost is also more or less equal for both calculation methods.

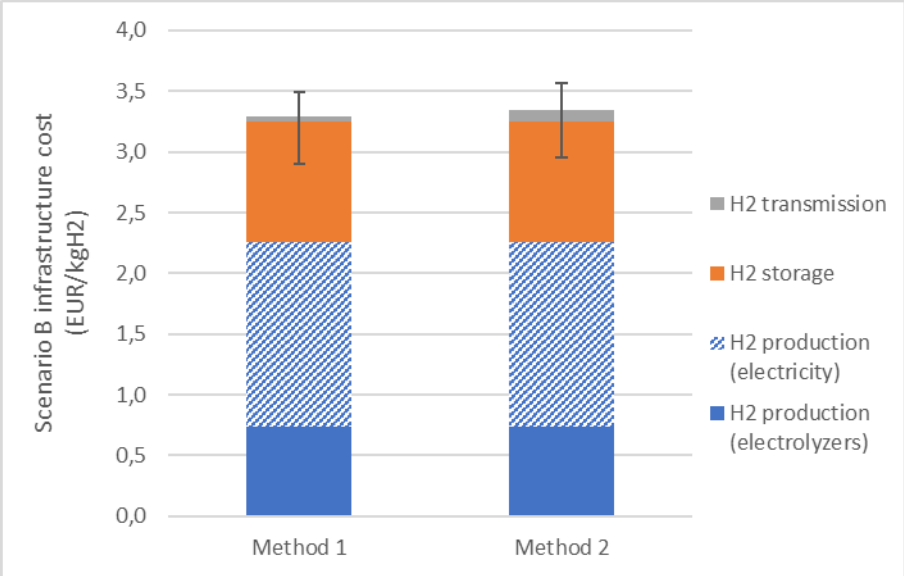

Figure 21. Total specific infrastructure cost for Scenario B using the two methods described.

All the assumptions and the results of cost estimations are presented in the following subsections. The reader is referred to Appendix 3 for the details about the calculations.

4.6.6 Hydrogen production

This estimation of the cost for producing hydrogen assumes that the wind farms are not connected to the national grid and that the electricity they generate is made available to stacks of electrolysers producing the hydrogen at the same site (the electrolysers operate only when wind turbines are generating electricity). According to the parameters summarized in Table 26, the cost for producing hydrogen would be in the range between 2.05 and 2.65 EUR/kg hydrogen.

Table 26. Main parameters used for calculation of hydrogen production cost

CAPEX of electrolysers	400 EUR/kWe	In between (Fraunhofer Institute, 2021; IRENA, 2020)
O&M of electrolysers	3% of CAPEX	(Reuß et al., 2017)
Electricity consumption	47.6 $kWh_e/kg\ H_2$	corresponds to a 70% efficiency of the electrolysers (IEA, 2019; Reuß et al., 2017)
Electricity cost	24–36 EUR/MWh	levelized cost of electricity for wind power, sensitivity range around 32 EUR/MWh(Energiforsk, 2021)
Wind farm capacity factor	0.376	equivalent to about 3300 full load hours/year
Lifetime	15 years	In between (Fraunhofer Institute, 2021; IRENA, 2020)
Discount rate	5%	

4.6.7 Hydrogen storage

This estimation of the cost for hydrogen storage assumes that, due to the intermittency of wind power generation and in turn of the operation of the electrolysers, 20% of the hydrogen produced at each electrolyser facility must be stored in lined rock caverns. This assumption is based on the shape of annual wind power time history from the EMHIRES data set (European Meteorological derived HIgh resolution RES generation time series for present and future scenarios, JRC) for Sweden in the year 2015, see Figure 22.

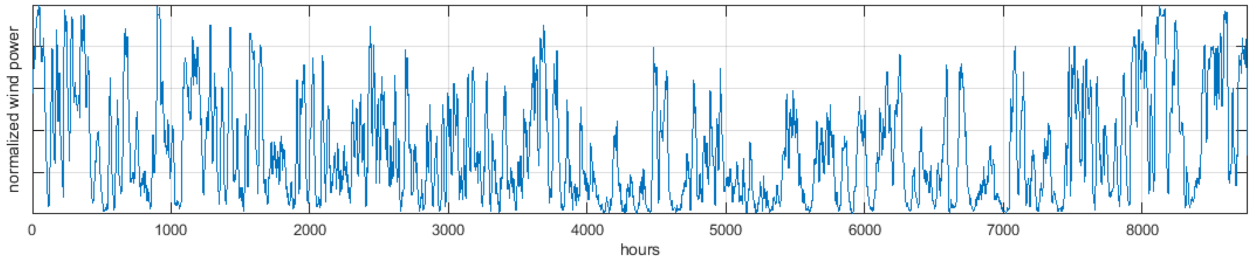

Figure 22. Annual wind power time history from the EMHIRES data set.

Integrating this time history and subtracting a constant demand in time that equals the annual production, a time history is obtained for the production that needs to be stored to compensate for the periods of over- and underproduction. Figure 23 clearly shows that 15% must be stored at some time during the year to have the storage empty only once at some other time. However, this refers to a specific year (2015), so a more conservative 20% is considered to take into account possible statistical variations within a year and compensations among years.

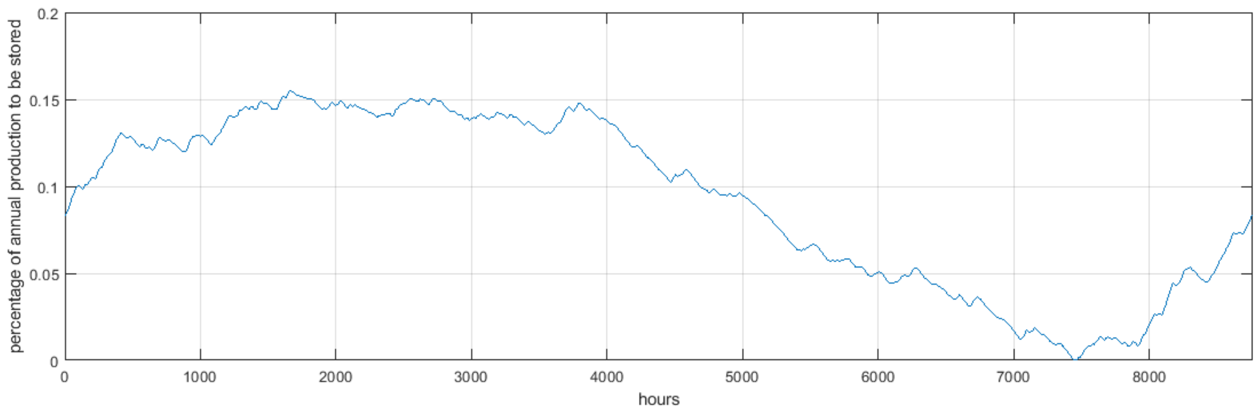

Figure 23. Storage capacity in percentage of the production over a year.

Line rock caverns are supposed to operate between 20 bar (minimum pressure) and 250 bar (maximum pressure), so that they can store 16.8 kg H_2 per m^3. To be stored, the hydrogen from electrolyser output (at atmospheric pressure) would have to be compressed to the current pressure inside the line rock cavern, which in turn depends on the current mass of H_2 stored. To avoid the details of line rock cavern operation, it is assumed that all the hydrogen produced by the electrolysers must be compressed to an average pressure of 135 bar (compression power required: 8.4 MW per kgH_2/s).

Other parameters used in the cost estimation are shown in Table 27.

Table 27. Parameters used in the cost estimation of hydrogen storage

CAPEX of lined rock cavern	55.4 EUR/kgH2	with max pressure 250 bar (Papadias and Ahluwalia, 2021)
O&M of lined rock cavern	2% of CAPEX	(Reuß et al., 2017)
Electricity cost	40 EUR/MWh	levelized cost of electricity from the grid
Lifetime	30 years	(Reuß et al., 2017)
Discount rate	5%	

The resulting estimated cost for hydrogen storage is 0.99 EUR/kg (29.74 EUR/MWh - see Appendix 3 for the details of the calculations at each station with electrolyser facilities).

4.6.8 Hydrogen transmission - pipelines

This cost estimation is based on the pipe diameters calculated in the section "Size of pipeline segments" and on the lengths retrieved from the QGIS software (see Appendix 3). Cost parameters used in the estimation are summarized in Table 28.

Table 28. Cost parameters for hydrogen pipelines

	Method 1	Method 2
CAPEX of pipes	According to diameter (See Appendix 3)	According to diameter (See Appendix 3)
O&M of pipes	0.8 - 1% of CAPEX	5% of CAPEX
Lifetime	40 years	50 years
Discount rate	5%	8%

The resulting estimated cost for the pipes is between 0.033 and 0.044 EUR/kg (1.00 - 1.32 EUR/MWh) according to Method 1 and between 0.079 and 0.125 EUR/kg (2.37 - 3.76 EUR/MWh) according to Method 2. The details of the calculations are available in Appendix 3.

It is worth noting that, at the average density of 7.4 kg/m^3, the mass contained in the pipes would be equal to about 1,180 t of hydrogen, equivalent to 39.3 GWh. With reference to the total mass of hydrogen to be delivered annually, this corresponds to a storage capacity of 6.5 hours (in the unrealistic hypothesis of extracting all the hydrogen from the pipes).

4.6.9 Hydrogen transmission - recompressing stations

Pipeline layout includes two recompression station, one in the city of Oulu (Finland) and one in the city of Boden (Sweden). In an actual recompression station, part or all the hydrogen coming from the preceding pipeline segment at 80 bar must be recompressed, the remaining part of the hydrogen that must leave through the next pipeline segment being taken from the local storage (which is at a pressure that depends on the mass of hydrogen currently stored in it). To avoid the details of line rock cavern operation, all the hydrogen mass flow rate that leaves to the next pipeline segment is assumed to be recompressed from 80 to 100 bar (the power required is 0.363 MW per kg H_2/s), no matter where it comes from. Table 29 shows the applied parameters in the two methods of cost estimation.

Table 29. Cost parameters for recompression stations

	Method 1	Method 2
CAPEX of recompressing stations	2.2–6.7 MEUR/MWe	According to required power (See Appendix 3)
O&M of recompressing stations	1.7 % of CAPEX	15% of CAPEX
Lifetime	25 years	15 years
Discount rate	5%	8%

The total cost for the recompression stations in Oulu and Boden is between 0.007 and 0.016 EUR/kg (0.21–0.49 EUR/MWh) according to Method 1 and between 0.006 and 0.009 EUR/kg (0.17–0.27 EUR/MWh) according to Method 2. The details of the calculations at each station are available in Appendix 6.

4.7 Techno-economic summary of the scenarios and sensitivity analysis

As previously mentioned, making accurate and precise long-term prognoses of the future are impossible. A useful approach is therefore to develop internally consistent scenarios, which can help to show possible long-term consequences of decisions made, serve as a basis for discussions and to understand drivers of a certain development. It is an illustration of how the future may look like, given certain assumptions, and where the interpretation of likelihood of realization is fully up to the viewer. In this section, a brief sensitivity analysis for some of the more important parameters that the scenario analysis has identified, to better understand their influence on the outcomes.

It can be concluded that the electrolyser OPEX (mainly electricity costs) dominates the hydrogen production costs. The CAPEX of electrolysers also constitutes a large share of the costs, since the relatively low-capacity factors (50% in A and 36% in B) require larger installed production capacities to fulfil the demand. It is also noted that the cost for transmission of both hydrogen and electricity via a hydrogen pipeline or a power grid constitutes a small share in relation to the estimated total infrastructure cost.

The annual operational hours of the electrolysers determine the amount of hydrogen produced per kW of installed capacity. Hence, the CAPEX per kg hydrogen decreases with increased capacity factor (blue curve in Figure 24). In contrast, the OPEX are mainly determined (except for very low hours of operation) by the electricity prices and, assuming the average prices of low-cost hours, OPEX (red curve in Figure 24) increase for higher capacity factors. Hence, the total electrolyser costs (black curve), i.e. the sum of CAPEX and OPEX, obtain a minimum, which for the assumptions made here is obtained at approximately 2500 annual operation hours. However, since, for scenario A, the assumed electricity prices were obtained from LMA2021 (Svenska Kraftnät, 2021), (Svenska Kraftnät, 2021), (Svenska Kraftnät, 2021), (Svenska Kraftnät, 2021), (Svenska Kraftnät, 2021), (Svenska Kraftnät, 2021), the electrolysers' operation hours were also chosen to be the same (4380 h) as in LMA2021.

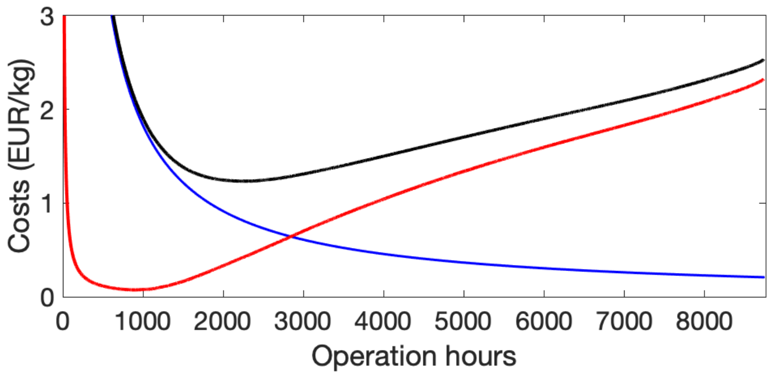

Figure 24. CAPEX (blue), OPEX (red), and CAPEX+OPEX (black) as a function of operating hours for electrolysers.

The pipeline system described in Scenario B is dimensioned based the hydrogen demands and on non-grid connected, wind-power based electrolyser units. Hence, relatively large storage capacity was found necessary. However, if, e.g., the plans for a Baltic hydrogen corridor are realised, significant amounts of hydrogen storage will be provided by the trans-continental transmission pipeline and central European salt caverns. If so, the need for storage next to the electrolysers could likely be significantly reduced.

A key parameter is the electricity price, which as described are not straightforward to estimate for 2050. For wind power, similar as for solar cells, batteries, and electrolysers, the learning curves suggest that costs will decline with the continued installations of new capacity. Recent expert elicitations suggest that costs for onshore wind power could be reduced by 30-40% from 2020 to 2050 (Wiser et al., 2021), which would imply that the mean LCOE for wind power in Sweden could be reduced from 32 EUR/MWh to 19-23 EUR/MWh. Of course, that cost reduction, which is to some extent is included in the LMA2021 from SvK, used for scenario A, would reduce the total costs of hydrogen. Assuming a mean LCOE of 21 EUR/MWh and 7 days of hydrogen storage, the resulting indicative LCOHs become similar for scenario A and B.

A detailed analysis also allows for investigating features that can be missed when considering only the total cost, where electrolyser CAPEX and OPEX dominate. One can note that not only is the CAPEX for transmission infrastructure, but also the OPEX lower for a hydrogen pipeline, including recompression stations, than for power transmission, under the given assumptions in scenarios A and B. Furthermore, for the sensitivity analysis with 7 days capacity hydrogen storage, the OPEX for the storage become similar to the storage CAPEX. Storage OPEX is also sensitive to electricity prices due to the energy demand for hydrogen compression.

To conclude, although the scenarios presented in this report are based on coarse descriptions of the hydrogen system; and despite necessary simplifications and assumptions and given uncertainties regarding future development regarding costs, they provide valuable insight on which factors that are most important to study in more detail. That knowledge, combined with proper analysis, also enable better understanding of the individual parts of the systems. However, to obtain deeper understanding of the different parts, and how they couple to each other and the energy system in large, more advanced and detailed energy system modelling are required.

4.8 Preliminary SWOT analysis

Preliminary SWOT analyses for the scenarios are presented in Tables 30–31.

Table 30. SWOT analysis for Scenario A: Power transmission.

	Strengths	*Weaknesses*
"Internal" factors	Proven and reliable transmission technology with vast locally available knowledge capacity There is no need expanding power transmission capacity from SE2 to SE1, given new generation in SE1 and electricity import from Finland The current transmission capacity from SE2 to SE1 can facilitate SE1 becoming a use node in the future Electrolysers can act as balancing agents and load regulators, providing systems services to the power grid.	Not enough renewable power available nor planned in SE1 – large electricity imports to the region likely to be required Additional electric storages, such as batteries may be needed to fully minimize under-utilisation of intermittent renewable power
"External" factors	*Opportunities*	*Threats*
	Enough planned new wind power generation in Finland to cover the SE1 demand Electrolyser by-products such as oxygen and heat can potentially be utilised on, or near, site. Improved business opportunities for wind power companies due to stable offset and increased value-factor	Insufficient power transmission capacity between SE1 and Finland Construction of several additional 400 kV transmission lines will have a large visual and direct impact on the landscape and land use The large reliance on wind power with its intermittency may affect the power quality of the power system negatively

Table 31. SWOT analysis for Scenario B: Hydrogen transmission.

	Strengths	*Weaknesses*
"Internal" factors	Little interference with the power grid - hydrogen production will support grid stability by "absorbing" the intermittent power production and reducing wind power curtailment Avoided costs for strengthening the grid capacity Excess power production is stored in the hydrogen Mild landscape interference and small land use areas occupied for energy transmission Flexible electrolyser/hydrogen production localisations	Hydrogen supply vulnerability at disruptions - no redundancy (unless complemented with minor storages at the user sides (which requires some overcapacity in the pipelines)) Large hydrogen storage volumes required Largely over-sized electrolyser units needed Difficulties to take larger future unknown demand changes into concern when dimensioning
"External" factors	*Opportunities*	*Threats*
	The resulting electrolyser residual heat production exceeds the complete district heating demand of SE1 (2.3 TWh per year) Improved business opportunities for wind power companies due to stable offset Good possibilities for other hydrogen actors, both hydrogen providers and users, to connect to a pipeline Possibilities to coordinate the pipeline construction with other infrastructure investments, such as Norrbotniabanan or the 6G network	Potentially low public acceptance for an underground pipeline Low local knowledge capacity regarding large scale gas infrastructures

4.9 Revision of REDII and potential effects on power and hydrogen balances in SE1

As discussed in the previous chapter, the revision of the REDII, and its article 27(3) defining the rules for electricity from the grid to be counted as renewable for hydrogen production, is an on-going process where the current negotiation positions of the Commission and the Parliament differs. In short, the not yet finalized proposal from the Commission aims for:

- Spatial correlation: the electricity should be produced in the same bidding zone, or in a bidding zone with equal or higher electricity price.
- Temporal correlation within the hour.
- The additionality principle with power plant not being added more than 36 months before or 24 months after the installation of the electrolyser.
- However, exemptions from the requirements above are made for bidding zones with more than 90% renewable power production, e.g. SE1 and SE2.

This can be compared with the Parliament's official position that do not mention the principle of additionality and suggests:

- Spatial correlation: the electricity needs to be produced within the same or a neighboring country.
- Temporal correlation between PPAs needed to be concluded and the electricity taken from the grid on a quarterly basis.
- However, no exemptions for bidding zones with high shares of renewable energy are suggested by the Parliament.

It is of interest to understand how the finalized revision of REDII may influence the energy flows due to the expected deficit in SE1 by 2030. We consider two cases, the first (Case 1) without the principle of additionality, which would correspond to the current position taken by both the Commission and the Parliament, since the Commission suggests exemption for bidding zones with high share of renewable energy. The second case (Case 2) assumes that the additionality principle and spatial correlation suggested by the Commission are applied also in SE1, as no exemption is mentioned by the Parliament.

If the additionality rule will be applied, the current power production is only allowed to be used to cover the estimated demand for electrons (i.e. not for hydrogen). Only new power production can be used for hydrogen production, leading to increased import of new power (or additional domestic production). However, the potential excess of the current power production can be exported.

Both for scenario A and B, the total power demand in 2030 is 53 TWh/year considering the estimated demand for electrons (22 TWh) and the power needed to produce enough hydrogen with 70 % electrolyser efficiency (31 TWh). In SE1, the current power production is 27 TWh/year, while the new planned power production amounts to approximately 13 TWh/year, in total 40 TWh/year.

Figure 25 shows how the power balances in Scenario A would be affected in 2030. In Case 1, the deficit in SE1 becomes 13 TWh (53 – 40 TWh). In Case 2, current power production may cover the demand for electrons, resulting in a net excess power of 5 TWh. But the production of renewable hydrogen needs import of 18 TWh additional renewable power (31 – 13 TWh). In Case 2, the spatial correlation requires that imports can only be made from bidding zones with similar or higher electricity prices. Historically, the spot prices are in general similar in SE1 and SE2 but higher in Finland. With the expected deficit in SE1, it is expected that the prices there will increase. If we assume that prices in 2030 on average are lower in SE2 than in SE1 and Finland, imports to SE1 will come from SE2 in Scenario A and Case 1, due to the lower prices in SE2. In contrast, in Case 2, the rules for spatial correlation require that imports for production of renewable hydrogen can only be made from bidding zones with similar or higher electricity prices. Hence, imports of additional renewable power will be made from Finland (likely at times when prices are only slightly higher than in SE1), and at the same time current (non-additional) power production could be exported.

Figure 26 shows the same circumstances for Scenario B, with the assumption that as much as possible of the available power production (in excess to the need for electrons) in SE1 is used locally to produce hydrogen. The remaining demand for hydrogen differs if current power production can be used for renewable hydrogen production, with a need for imports of 9 TWh hydrogen (corresponding to 13 TWh electricity) in Case 1, and 13 TWh hydrogen (18 TWh electricity) in Case 2. In Case 2, there is an excess of current power production, which could be exported, e.g. via SE2 to southern Sweden or the continent.

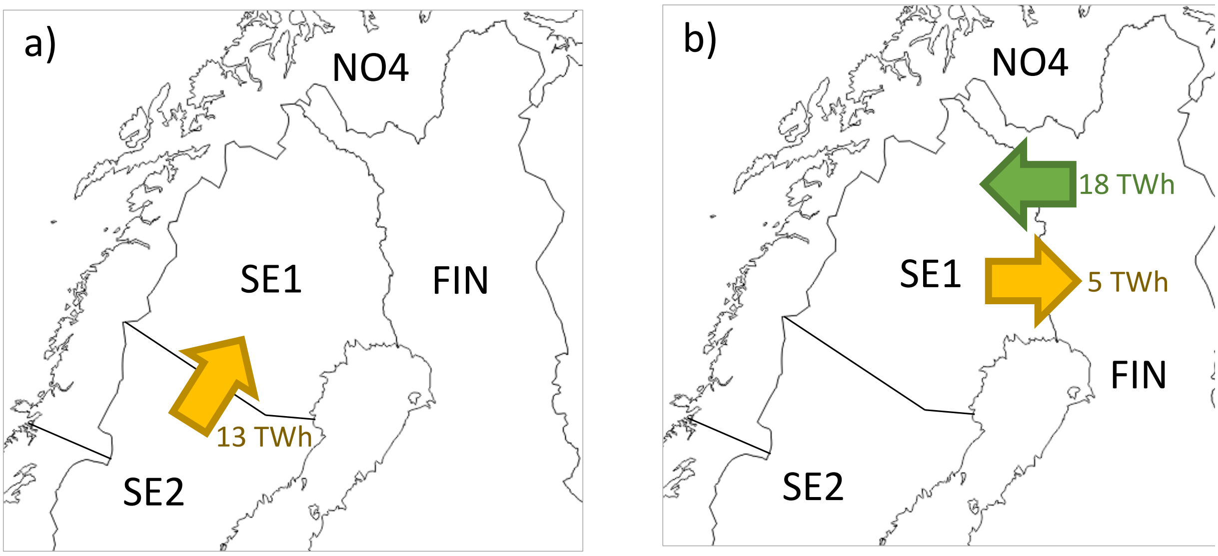

Figure 25. The flows of electricity for Scenario A in Case 1 (a) and Case 2 (b) in 2030. The green arrow means additional renewable electricity and yellow arrows mean current electricity production.

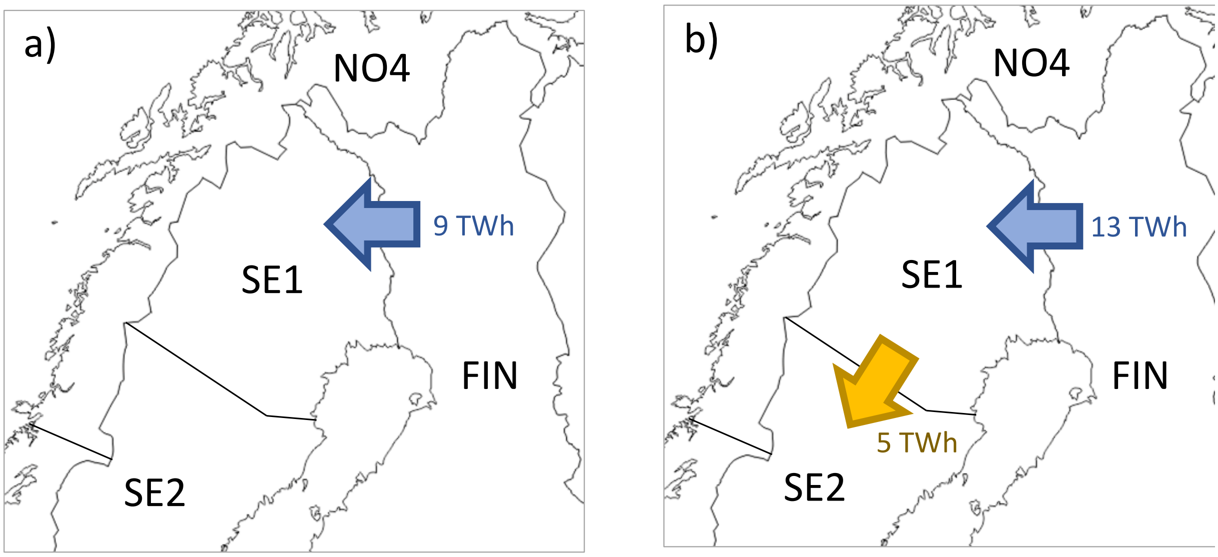

Figure 26. The flows of electricity and hydrogen for Scenario B in Case 1 (a) and Case 2 (b) in 2030. Blue arrows mean renewable hydrogen and the yellow arrow means current electricity production.

In both scenarios A and B, the details of the revised REDII may have a fairly large influence on the electricity flows across the SE1 boundary and thereby also affect how the supply system in both scenarios should be dimensioned. For both scenarios, the required imports (and surplus current production for export) of renewable power or hydrogen increase by 5 TWh/year if the stricter rules (Case 2) are applied.

Additionally, the position of the Parliament, that PPAs are required could possibly also, if long-term PPAs with fixed electricity prices are entered into, reduce the incentives to operate the electrolysers flexibly, which not only reduce the services that could be provided to the grid, but also could lead to higher production costs for hydrogen (by up to ca. 30% according to the sensitivity analysis presented in this chapter) if low-cost spot prices are not fully utilised.

4.10 Summary

- A substantial increase in energy demand can be expected in SE1, due to the planned industrial investments in hydrogen-based iron and steel making and in production of renewable ammonia.
- The future demand of renewable hydrogen in SE1 is estimated to exceed 20 TWh per year already in 2030. In 2040, the demand is predicted to be doubled (41 TWh per year) and to go beyond 50 TWh per year ten years later in 2050.
- If all the renewable hydrogen needed is assumed to be produced via electrolysis with a conversion efficiency of 70 %, more than 70 TWh per year of renewable power will be needed. This corresponds to almost 45 % of the current Swedish total electricity production (Energimyndigheten, 2022).
- The additional electricity demand in SE1 used for other purposes than renewable hydrogen production is estimated to 23, 31 and 36 TWh per year for 2030, 2040 and 2050, respectively. On top of that, the remaining demand for other energy carriers (such as solids, liquids etc) is estimated to be relatively constant around 17-18 TWh per year in the same time span.
- Despite the significant demand increase, it seems likely that there will be enough renewable power production in the studied region to fulfil the future demands for both hydrogen and electricity.
- To a large part, this is due to the extensive plans for new wind power investments on the Finnish side of the region (> 100 TWh per year), in which a large share of the required demand in SE1 (for direct transmission or hydrogen production) can be produced.
    - In Scenario A it is estimated that in 2030 around 13 TWh of renewable power imports from Finland (or elsewhere) would be needed. This could grow to in the range of 28-43 TWh per year in 2040 and 28-53 TWh per year in 2050.
    - In the Scenario B for 2030, approximately 14 TWh per year of hydrogen could be produced in and imported from Finland. This corresponds to around 20 TWh per year of renewable wind power with assumed electrolyser efficiency which is significantly less that new planned wind power production.
    - The hydrogen imports need to increase with time and in 2050, it is estimated that close to 30 TWh per year may need to cross the border. 43 TWh per year of renewable power would be needed for that - still significantly below the planned new production capacity.
- The present power transfer capacity between Finland and Sweden is however too small for the required import demands in Scenario A – the transmission capacity must be enlarged around three times to cope with the required imports in 2030.
- Even with a pipeline system supplying the complete demand of hydrogen, the existing power transmission grid to areas of Kiruna, Gällivare, and Luleå are likely insufficient to supply the power demand.
- With proposed pipeline design in Scenario B and during normal operation
    - The storage capacity in the pipeline can be seen as a buffer, up to maximum of a few days to cover the full demand in 2050.
    - The pipeline can however not be relied on as a buffer to store the seasonal over-production from wind power on the supply side.
- The design of the proposed additionality rule in the forthcoming RED III may have a large influence on required infrastructure investments in both Scenario A and B.
- The costs for hydrogen production and storage are dominating, while the cost for transmission, using power grid or hydrogen pipeline, are marginal.
    - The lower infrastructure cost per kg of delivered hydrogen in Scenario A is the result of an assumed higher utilisation factor for the electrolysers combined with a similar cost of input electricity (which in Scenario A includes the cost for storing some of the

overproduction of the large share of wind power introduced in the energy system in the existing hydropower facilities). Scenario B is also penalized by the cost for the large, lined rock caverns required to store the seasonal overproduction of hydrogen from the electrolysers.

  - Rather than focusing on transmission, it would be advisable to focus on how the hydrogen is produced and stored, i.e., to come up with consistent overall assumptions on the hours of electrolyser operation, duration curves of the electricity price in those hours and suitable storage options for either hydrogen or electricity (in the latter case these options should be consistent with the assumption on the electricity price) in order to minimize the costs of the delivered hydrogen.

- More efficient land use with a pipeline system – also good opportunities to coordinate with other infrastructure investments, i.e., Norrbotniabanan, 6G network etc.
- It is likely that the supply system described in Scenario A can be realised. This scenario describes, more or less, the activities and plans that have, at least until now, been communicated by the industrial stakeholders.
- It is on the contrary less likely that a pure pipeline supply system as described in Scenario B, for many reasons, can or will be realised.
- However, based on the many technical benefits that a pipeline system may bring, large and fast efforts should be put on developing a hybrid system to avoid unnecessary lock-in effects. There is a great potential for the two supply methods to complement each other in an energy and cost-efficient way. This prestudy project has paved the way for such an effort.

5 Definition and outlining of research questions for further work

This chapter defines and outlines the topics that need to be further investigated in research projects or investigations. It also discusses which type of actor (research institute, academia, consultant, etc.) should be dealing with each topic with an aim to form a basis for future decisions by stakeholders and policy makers who are involved in one way or another in the development of the hydrogen and energy sector in the region.

5.1 Introduction

The project behind this report was motivated by the planned large-scale industrial processes in Norrbotten that will use substantial amounts (> 1 million ton/year) of fossil-free hydrogen to produce fossil-free steel and ammonia. The assumed source of fossil-free hydrogen is primarily water electrolysis using fossil-free power from electricity bidding zone SE1. Some of that power may be imported from northern Norway and Finland.

Water use for hydrogen production can be a serious issue in some parts of the world. However, in Norrbotten the availability of water is very high and the total estimated annual use corresponds to the flow from Lule river during app. 3 hours. In addition, there are several other large rivers in the county.

After the project started, a war broke out in Ukraine followed by an economic conflict between the EU and Russia that has led to a disruption of the energy supply to the EU. This has raised the awareness of the need for better security of energy supply and how this could be helped by the development of a hydrogen grid.

In the following pages, recommendations are given for continued research and development to support the on-going industrial development. However, it should be remembered that the companies that are involved in this development already carry out a massive amount of research and development and business development. Our proposal is not meant to replace this but instead complement it in areas where publicly funded research and development can make a difference and where other proposed activities can support the development.

The key question that this project set out to answer was if it is possible to reach a better total system efficiency by combining the existing power grid with a new hydrogen infrastructure in the region (northern Sweden, northern Finland, and possibly also northern Norway). The short answer to this question is that there are several advantages with a combination of the power grid and a new hydrogen grid but also many uncertainties (see Chapter 4). The purpose of the current chapter is to sum up such questions and to make an outline of the work that could be done to support the ongoing industry projects.

The present project has, in addition to the results from the work in the project, used results from the proposal for a Swedish hydrogen strategy (Swedish Energy Agency, 2021b) and the synthesis report about the role of hydrogen in a fossil free society from the Royal Swedish Academy of Engineering Sciences (IVA, 2022) as input for the analysis in the present chapter. A summary of the main findings of these two reports can be found in Appendix 7 and Appendix 8.

The goals of this chapter are to define and outline a work plan aimed at (1) speeding up the transition to a hydrogen energy system in north Sweden and Finland, and (2) contributing to the decision basis for a possible future infrastructure for transmission of hydrogen gas. The target groups of the chapter are industries in the hydrogen value chain, academic actors from universities and institutes, public sector organisations and companies, politicians and funding agencies.

5.2 Research needs and obstacles for development

The present chapter used the results from the interviews in combination with the analysis on regulations and the results from the system analysis to identify major factors that must be addressed to ensure a rapid development regarding hydrogen-based systems. These factors are listed in Table 32.

The reader is advised to read this in parallel to the take-aways from the interviews, listed in sub-chapter 2.2 and Appendix 2.

In Table 32, the research needs for different steps in the value chain for hydrogen, and for general questions including health, safety and acceptance are listed. The text that follows has the same order as in the table. The most prioritized research needs are indicated with bold font. A more detailed discussion of these topics comes in the following sections, including suggestions of actions. Notice that the research needs relating to the use of hydrogen in metallurgical and chemical processes are excluded from the present discussion since they are the responsibilities of others. *The list in Table 32 needs continuous updates and completion to remain coordinated with the current rapid development in the hydrogen area.*

5.2.1 Research and development needs

Evaluation of further scenarios and cases

The top priority seen from the perspective of the present project is to develop a much better **understanding of an energy system where hydrogen pipelines are an integral part** of the architecture. To achieve this, questions related to hydrogen pipelines must be addressed. In particular, there is a need for further development of system models of combined power and gas systems and to use them to explore different system design scenarios. In Chapter 5, two extreme scenarios (thought experiments) have been evaluated: (A) Production of the hydrogen on-site and enforce the power grid and (B) Production of the hydrogen “on” the wind farms and transport of hydrogen in pipelines. The conclusions from the evaluation of the results are that there are pros and cons with both these extreme scenarios and a combination of them would most likely be more advantageous from several perspectives. Therefore, there is a need to evaluate additional hybrid scenarios (cases), which are all possible to realise. Realisation of such a scenario would mean that an enforcement of the power grid is complemented with a number of connected pipelines. Continued studies should compare several alternative scenarios to get a better perception which would be the most advantageous solution.

Fluid dynamics in pipeline systems

There is also a need for a better **understanding of the fluid dynamics and transient characteristics of pipeline systems**, including interaction with underground storage volumes and the impact from sudden variations in production and use of hydrogen.

Design of lined rock caverns

Moreover, there is a need for new and improved tools for the **design of lined rock caverns** in different types of rocks, including the effect of faults and imperfections in the rock. This means that there is a need for hydrogen storage research in the field of rock mechanics.

Hydrogen is a difficult gas to work with both from a **safety** point of view and with respect to its interaction with materials (e.g. hydrogen embrittlement but also transport of hydrogen from leaks through metal, rock and soil). **Material science** connected to pipeline systems with lined rock caverns in **cold climate** is therefore a high priority as well as **underground diffusion** of hydrogen. **Safety** related issues connected to the future hydrogen system are also a high priority.

Table 32. Research categories and other needs identified with respect to hydrogen pipelines in northern Sweden. Bold text is considered especially important.

	Energy sources and power supply	Hydrogen production	Distribution	Storage	Use	General
R&D needs with respect to hydrogen pipelines	**Optimal design of power systems combined with a hydrogen grid**	**Use of equipment and optimal operating strategies in cold climate**	**Large-scale distribution systems in cold climate**	**Lined rock cavern storage**		**Hazards, environmental impact, land use**
	Optimal system solutions, with or without hydrogen infrastructure, evaluation of multiple scenarios					
	Analysis of System Integrity Protection Schemes[110] involving large-scale hydrogen systems					
	Safety of very large systems, differences to existing small scale systems					
R&D needs general	**Issues connected to power grids with very large variable power production**	**Lowering the cost of electrolysers** is crucial according to the preliminary system analysis	Fluid dynamics and control theory. Computer modeling of hydrogen pipeline systems.	Using electrofuels (e.g. ammonia) for hydrogen storage	Use and valorisation of waste heat and oxygen	**Legislation. Political instruments. Underground diffusion of leaked hydrogen.**
	Health and safety					
	Environmental and sustainability impact of the proposed systems					
	Material science, both metals and polymers in contact with hydrogen					

[110] Svenska: Systemvärn eller nätvärn

Innovation	Selection of optimal production sites and development of tailor-made system solutions	Many technology vendors with several different types of technology on the market. Security of supply is OK since several of them are Scandinavian	Optimal system solutions with or w/o hydrogen pipeline infrastructure. Investigate hydrogen infrastructure as a complement to the power grid.	Large scale storage technical development and verification needed	World leading companies are developing the technology, therefore no need for general research in the established areas	Safety, also related to differences against existing hydrogen systems
	Development of reserve power solutions with peak power units or flexible demand	**Large scale electrolysis systems in cold climate are unique for Sweden and there is a need for innovations to minimise costs and energy use**	**Large scale distribution systems for hydrogen in cold climate**	**Development of "hydrogen proof" materials**		**Proof of concept of material, sub-components, components and systems**
Competence	Need for a large number of people with relevant competence. Graduate engineers and re-skilled professionals from other industry sectors as well as up-skilled own employees					
	Acceptance of large hydrogen systems by the public is crucial. This requires public education and objective information					
Co-operation for a developed value chain	Optimal design of power systems with very large fraction of wind and solar power	Local or regional development and production capacity of electrolysers and sub-components	**Implications of different ownerships requirements**	Development of methods to calculate storage needs including backup need and other factors	Use of oxygen and waste heat on production and energy conversion sites	
Development of regulatory framework		Investigate the implications of the different taxing rules for different actors and localization of production	**Analysis for decisions on technical regulations and guidelines for pipelines, hydrogen plants**			Obstacles connected to legislation and political instruments.
	Shorten time and processes for permits					
	Integration of hydrogen systems into various SIPS solutions (System Integrity Protection Schemes)					
	Optimal design of an interacting hydrogen gas and electricity market, harmonised with the global market design **Analysis of import and export and their impact on Swedish security of supply**					

Electrolysers and pipelines in cold climates

A special problem with large scale production of hydrogen in the region of Norrbotten and northern Finland is that the climate is cold, meaning risk for sub-zero temperatures, at least half the year. Extreme cold temperatures (< 40 C) are also possible, and a robust industrial process must be able to function in all conditions. A complicating factor in this connection is that most contemporary installations of electrolysers rely on strong forced ventilation to ensure that any leakage of hydrogen is quickly diluted below the flammability limit, which is extremely low for hydrogen. In warmer climates this is not a problem but in cold climates this may lead to freezing of feedwater and other unwanted side effects that can disturb the stable operation of the electrolysers. One way to deal with this problem is preheating the ventilation air to the electrolysers but this could lead to excessive costs for heating. Hence, there is a need for research aimed at **improving the heating economy,** for example by efficient recovery of waste heat from the hydrogen production and outgoing ventilation air, while maintaining the **safety of the buildings** housing the electrolysers. The systems might be designed differently depending on where the electrolyser is placed in relation to the site where the hydrogen is used, which in turn depends on the realization of gas pipelines.

Fluctuations in power production and demand

It has been assumed by many that a combined power and hydrogen system will be more resilient to **fluctuations in power production**. However, this presupposes that the power system can tolerate arbitrary large fractions of variable power generators and sudden changes in the load. In reality, there is a limit to how much variable power one can connect to the grid without impact on the power quality and stability of the grid. Potential problems are voltage peaks and overtones in the AC system that can destroy sensitive technical equipment that is connected to the grid. It is also unclear what the impact on the power quality from connection/disconnection of very large electrolyser plants will be since this is a new component in the power system. More research is therefore needed on the **behaviour of the power grid** in such a situation with an aim to set limits on how much variable power can be connected and how the combined power and hydrogen grid can be designed to improve the tolerance to variable power sources and loads.

System Integrity Protection Schemes (SIPS)

Transmission grids are dimensioned according to the so-called N-1 criterion, which means that operation should not be jeopardized by the disconnection of one arbitrary part of the power system. If a consumption area is fed from a production area via N (e.g. 5) parallel transmission lines, their maximum combined capacity is based on the capacity of N-1 (i.e. 4) lines. In cases where the available transmission capacity is not enough, the most robust measure is to physically increase the capacity with stronger or more wires. This may however take more than a decade from decision to commissioning, therefore other alternatives need to be considered to meet the agility of the societal developments. A relevant alternative is so called **System Integrity Protection Schemes (SIPS)** which are automatic systems used to increase the transfer capacity of the transmission grid without decreasing of the security of supply (Stankovic et. al. 2022). In a simple way, a SIPS can enable utilisation of the grid over the N-1 criteria based on monitoring and control of dedicated resources. Integration of hydrogen systems into various SIPS solutions, could strengthen the security of the grid as well as increase the transfer capacity during strained situations. Additionally, SIPS should be considered as a grid strengthening solution when planning the installation of an electrolyser plant to limit the need of physical strengthening of the power grid to the plant. The realization of hydrogen infrastructure will have an impact on how SIPS can be used to strengthen the power grid. More research is therefore needed in this area.

Valorisation of by-products - waste heat and oxygen

Production of green hydrogen by electrolysers will result in large amounts of by-products, waste heat and oxygen. To make hydrogen production from electrolysis more profitable, and to increase the overall efficiency of the energy system there are ongoing studies about using waste heat from electrolyser and other sources of low-grade waste heat for many different applications such as other industrial processes, heating green houses, farming meal worms, drying fruits etc. The waste heat could also be used for district heating, which would be particularly important in the municipality of Luleå that is currently heated with waste heat from the coke oven at the SSAB steel mill. However, the temperature of waste heat from electrolysis is relatively low and not very valuable to use directly for district heating, without combining it with heat pumps or booster boilers.

The possibilities to valorize the waste heat and oxygen, will be dependent on where the electrolyser is placed in relation to buildings and other industries and businesses. A realization of a hydrogen infrastructure will give much more freedom in where to place the electrolysers in relation to the hydrogen demand. Further research is therefore needed in this area.

A large fraction of the oxygen from electrolysis could be used in a process for conversion of biomass to valuable products, e.g. biojet, biomethanol or biodiesel. The oxygen would in that case be used for oxygen blown gasification, and this use would eliminate the need for an air separation unit with a large reduction in the overall CAPEX for the process. Such a process would also benefit from using some of the hydrogen from a hydrogen grid. More than a doubling of the yield is possible if an optimum amount of hydrogen is added. It would again be an advantage if the electrolysis process was located in the vicinity of the biorefinery, and a hydrogen pipeline would give more degrees of freedom for this.

5.3 Innovation

It is a severe situation globally where the not yet fully proven hydrogen technologies are requested and planned to be installed at a very quick pace. Parallel technology development in line with the implementation is ongoing. This is a question of the lifetime of components, production capacity and material selection.

A characteristic feature in northern Scandinavia and Finland is the cold climate, which can be both a benefit (easy cooling) and a drawback (risk for freezing of feedwater lines). There is a need for development of appropriate system solutions, using components that have been developed elsewhere and with different environmental constraints.

In addition to the cold climate there are several other constraints that must be satisfied by the hydrogen system in order to meet the demands of the end users (high reliability, high availability, low sensitivity to variable power production, low cost etc.).

It is the responsibility of the industrial companies to develop these system solutions but judiciously chosen research by universities and institutes as well as collaboration among the companies will speed up the development. Public sector decisions, e.g. about a possible concession for an open hydrogen infrastructure, will also have an influence on the speed of development.

5.4 Competence

It will be a significant challenge to fill all the positions that are needed for the realisation of the plans for fossil-free steel in Norrbotten. Only considering LKAB and H2 Green Steel, there is a need for around 4,500 new employees in the coming decade (SVT, 2021). In addition, there will be a need for many additional jobs in other industry sectors, e.g. energy companies and sub-contractors to the steel industry. Some of these employees need to know a lot about hydrogen technology, some a little less. Hence, there is a need for education on several different levels, aimed at university programs in engineering, continuing education of already employed staff and re-skilling of people with a background in other jobs. The needs are so large that it will be difficult for a single actor in the educational sector to cover all of them. Thus, there is a need for national collaboration in the area of professional education.

Another important task is public education, aimed at increasing the understanding of the importance of the new technology for reduction of emissions of greenhouse gases and the need for more fossil free power production. There is also a need for information about risks and how they can be managed through various safety measures. Without a public understanding of the technology and how the risks are managed, there is a large risk for unfounded public opposition to the plans. It is important for the credibility of this information that it comes from an objective source without a direct economic interest in the development.

5.5 Development of regulatory framework

In Chapter 3, a thorough investigation of legislation related to the hydrogen system is recommended, e.g. a Swedish Government Official Report (SOU) or a national coordinator for authorities handling permits related to the hydrogen energy system. Furthermore, a national strategy for hydrogen, based on the current proposal, should be developed. However, it should also be considered if some issues need to be prioritized and investigated in short-term, e.g. a revision of the Natural Gas Act to include concession and TSO for hydrogen pipelines. Hence, in addition to more thorough investigations, each actor needs to consider which issues they could improve to facilitate the development of a fossil-free hydrogen system. For example, industrial actors should be encouraged to develop regulations and standards, and together with politicians provide the Swedish perspective in development of EU's regulatory framework.

In addition to the need for regulative developments above, we see need for further investigations of:

- An in-depth legal analysis of the proposed EU gas market legislation and how it will affect the Swedish legislation and gas market.
- Experiences and examples from other countries on regulations for the hydrogen system, and how they can be applied or modified for the unique conditions in Northern Sweden.
- The effects of the different definitions (sustainable and renewable) selected to make projects eligible for national and EU grants and, thus, on the energy system.
- The design of policies, and their effects on financial instruments, to enable a renewable hydrogen system that facilitates the transition in general, and to fossil-free steel in particular.

5.5.1 Market design

Development of an efficient hydrogen market

The development of a common hydrogen distribution infrastructure will integrate production, off-takers, and storage over a large geographical area. Different actors may utilise the infrastructure for selling or buying hydrogen or to provide storage services. As a result, the infrastructure will create a hydrogen market.

The magnitude of the hydrogen that will be produced and used, as well as the strong interlinking with the electricity market creates a need for considering the functioning of the hydrogen market in close detail. The very large installed electrolyser power along the hydrogen infrastructure, transactions on the hydrogen market (i.e., turning on and off electrolysers) will affect the electricity market over a large geographical area.

The still unformed hydrogen market provides an opportunity to design an efficient market framework fit for the future through appropriate policy instruments, rules, and regulations. Furthermore, the question of a hydrogen marketplace in northern Scandinavia and Finland is linked to the development of related legislation in the EU. However, to participate in the work at an EU level, it is necessary that we establish an independent understanding of the matter at hand.

The work to identify an efficient market design, trading platform and legislation will involve a wide range of topics. Below, we have outlined a few aspects which should be considered.

Identify and outline actors, potential for market abuse

The future hydrogen market is likely to contain a range of different actors and stakeholders. It is likely that there will be a conflict of interest between different actors and between actors and society.

Furthermore, the hydrogen market is likely to be characterised by a limited number of, predominantly large actors. One of the key issues to consider in market design is the potential for actors to abuse the market, leading to inefficient prices and an inefficient societal outcome.

Hydrogen marketplace and links to the electricity market

Most of the hydrogen is expected to be produced by electrolysis, i.e., using electricity. The hydrogen market and the electricity market will therefore be linked. How will this link between hydrogen and electricity market work and how will the hydrogen production and trading affect the electricity market? Will the marketplaces for electricity (NordPool) and hydrogen be integrated or separated from each other? The different alternatives must be identified and analyzed.

Flexibility and ancillary services

The hydrogen production can be flexible if it is combined with storage and has the potential to support the electricity system. We need to have a better understanding how a hydrogen infrastructure may affect the possibilities to offer flexibility. For example, a hydrogen infrastructure opens up for a distributed hydrogen production. That means that there will be more geographical sites where flexibility services can be offered.

Pending on the design of the marketplace, it may support flexibility to different degrees. A marketplace designed for flexibility would enable actors to offer flexibility as part of the auction.

The preferred design of a hydrogen marketplace

The preferred design of a hydrogen marketplace relates to the discussion above. The purpose of a marketplace is to match supply and demand in an efficient way. To create an efficient marketplace, the actors' needs must be fulfilled, as well as the socioeconomic aspects. One approach to study the coming hydrogen market is to proceed from existing energy markets to see if experience could be transferred to the hydrogen field.

5.6 Economic incentives

In the suggested national hydrogen strategy, the need to investigate incentives to fill the gap between fossil gas and fossil-free gas was already listed as an action. In the work with this report, the following was specifically requested by the stakeholders. First of all, counterproductive political instruments and taxes, i.e. several types of government actions that work against each other, must be eliminated. As mentioned above, the Swedish regulations are not updated for the introduction of a hydrogen energy system. When making this update it is of high importance that a comprehensive approach is used, and the responsibility for this could be dedicated to a certain agency or similar.

A functional economic set-up that stimulates competition and makes it possible for the market actors to find profitable business cases is also of importance. This would start with establishing the conditions and legal framework for well-functioning and well interacting markets for electricity and hydrogen. As suggested above, further research is needed in this area to provide appropriate information to policy and other decision makers.

For a flourishing hydrogen market to be established, sufficient profitability for all links in the hydrogen value chain is needed. This should be taken into account, when the overall framework related to hydrogen is set.

Last but not least, a pivotal condition for the further development is that good conditions for funding large public and private projects are secured.

5.7 Draft work plan for supporting actions, investigations and research

5.7.1 Alignment with the proposed Swedish hydrogen strategy

In the proposal for a Swedish Hydrogen Strategy these five points were the guiding principles:

1) The use of hydrogen will contribute to the transition to fossil-free solutions
2) Hydrogen will be used where it is economically efficient and does the most system benefit
3) Security of supply to be strengthened
4) Sweden to be a forerunner internationally
5) Sweden to export climate-smart products and services that contribute to fossil freedom abroad

The first two points are already concluded fulfilled when hydrogen is selected to be used in the hard-to-abate-industry sector in general and for fossil-free steel and e.g. fertilizers. The focus in this chapter is therefore on point 3-5. Having these three principles in mind, the findings are classified into the following four suggested areas for actions to achieve the goals of the strategy:

a) Research, innovation and competence
b) Co-operation for a developed value chain
c) Development of frameworks and regulations
d) Economic incentives

Further selected relevant writings from a pipeline perspective from the proposal for a Swedish hydrogen strategy (Swedish Energy Agency, 2021b) are listed in Appendix 8.

Political and national level

When combining the guiding principles 3-5 with the action areas a-d listed above, to define the deliveries of this report, the matrix in Table 33 could be set as a guide for prioritization of the continued work from a society perspective.

Table 33. Methodical selection of future work based on the guiding principles (columns) and action areas (rows) within the proposal for a Swedish Hydrogen Strategy by the Swedish Energy Agency, 2021.

Application on focus areas from the suggested Swedish national hydrogen strategy on the work focusing on the value chain around hydrogen pipelines in this report	**Security of supply to be strengthened**	**Sweden to be a forerunner internationally**	**Sweden to export climate-smart products and services that contribute to fossil freedom abroad**
a) Research, innovation and competence	Evaluate advantages with security of supply, of local renewable energy production, compared to import, and different hydrogen storage and distribution options, and spread the knowledge.	Develop applicable research and education programs. Develop top-class education material and plans to spread the knowledge. Include new research areas into the subject, including economics, business development etc.	Investigate and develop the value chain based on national and international perspectives. Use innovation for further development and results.
Suggested stakeholders	*National agencies, including defense*	*Funding agencies, universities, research institutes*	*Supporting organisations, Business Sweden, national agencies*
b) Co-operation for a developed value chain	Involve further stakeholders, such as the stakeholders in the defense area. Co-operate with the closest stakeholders in Finland, and the Nordics.	Select the top-level co-operation partners. Particularly important are partnerships in areas where Swedish industry is weak, e.g. production of electrolysers. Search for collaborations where traditional Swedish strong areas, e.g. system solutions, are important.	Evaluate where to work on national resources, contra where international co-operation possibilities are preferred. Organize dialogues with agencies, where it is a lack at the present, within and across borders.
Suggested stakeholders	*Public actors*	*National agencies*	*All*

c) Development of frameworks and regulations	Rules and regulations regarding ownership of pipelines must be formulated with security of supply in mind. Foreign ownership is undesirable.	The permission process can jeopardize the goal of being a forerunner if it is too slow. The national agencies that are responsible must have sufficient resources (personnel and sufficient funding).	In addition to implementing appropriate national rules and regulations to speed up industrial development we should participate in international frameworks to do the same.
Suggested stakeholders	*National agencies, government*	*National agencies, government*	*National agencies, government*
d) Economic incentives	There must be a price on security of supply to create an incentive for the industrial actors to contribute to this. Frameworks which enable the realization of an efficient and robust market design for a hydrogen market, connected to the electricity market	Industrial participation in applied research projects must be stimulated. Sufficient funding for these types of projects must be in place.	Review existing support to the export industry (credits etc.) and make sure that the hydrogen economy qualifies for support.
Suggested stakeholders	*Government*	*Funding stakeholders*	*National agencies*

5.8 Recommendations for continued work by universities and institutes

In the recommendations for future work, we have tried to find a way to support both the industrial developments in Norrbotten and the strive to develop a more robust fossil-free energy system on a national level. Further co-operation is needed on a high level between national agencies, companies, universities, institutes and public partners for implementation, planning and to set the strategies.

5.8.1 Education

In the discussion above it was mentioned that education is needed on four different levels (university engineers and PhD's, up-skilling, re-skilling and public). To stimulate the development of courses and programs by the different actors one university could be assigned as the national contact point for hydrogen-related education to coordinate the work. The aim of the work should be to increase collaboration and communication among the different actors with the ultimate goal to increase the number of trained professionals in the area.

5.8.2 Research

The preliminary system analysis that has been done in this project indicates that an integrated hydrogen and electricity system has many desirable advantages compared to a system with on-site production of hydrogen only. However, the knowledge about hydrogen pipelines in Sweden is limited, which can become a limiting factor for rapid deployment of such a system. **We therefore propose the initiation of a dedicated research programme focusing on hydrogen pipeline technology and its application in a combined hydrogen-electricity system**. Research is needed in several sub areas, e.g. material science, rock mechanics, fluid mechanics, system analysis, safety analysis, legislation, electric power system in strong interconnection to hydrogen production, valorization of by-products such as heat and oxygen, market design research etc. The best way to organize such a cross-disciplinary research programme is in the form of a graduate school, in collaboration with research institutes, which in addition to research also should develop courses of common interest to many students. Such courses will also be valuable for undergraduate education and should be offered to PhD students outside the program. Through this dedicated program, a number of experts will become available to the industry within 4-5 years. In addition, a similar number of senior staff at universities and institutes will increase their knowledge in the area. This will improve the quality of both graduate and undergraduate education and increase the number of professionals in the area over a longer period. The collaboration between universities and research institutes will intensify knowledge transfer to industry and give access to and strengthening of expertise in the institutes. The university supervisors and experts from the institutes will also be available as experts to government agencies who need independent advice to that which can be obtained from industry. A graduate school is a well needed long term investment. However, several decisions need to be taken and several activities need to be performed within the years to come, rather soon. Therefore, a graduate school should be complemented with a cross-disciplinary research programme to fund research performed by senior researchers from academy, institutes and consultancy firms. Such a research programme should ideally be set up and performed in collaboration with the other Nordic countries, with similar plans and strong interest in this field.

5.8.3 Other activities

In addition to teaching and research there is a need for many other activities if the implementation of a combined electricity and hydrogen system shall be rapid. Some of the activities needed have been discussed above (development of efficient rules and regulations, rapid permit process etc) but more needs will probably be identified later. We do not propose any particular action to speed up the work in this report but want to point out the need for further actions from one or more government agencies and from the political system.

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Appendix 1. Key stakeholders in Sweden, Norway and Finland

Power grid, trade and production

- Vattenfall
- Skellefteå kraft
- Luleå Energi
- Fortum
- Uniper
- Statkraft
- Lokala

Wind power

- W3 Energy
- Lhyfe
- Fu-Gen
- Wpd Offshore
- Svea Vind Offshore
- RES
- …

H_2 distribution & storage

- Nordion Energi
- Linde Gas
- …

Industry

- LKAB
- SSAB
- H2 Green Steel
- Hybrit
- Fertiberia Group
- …

Fuel

- St1
- Liquid wind
- Pulp and paper
- …

Transport

- Skoogs
- Zelk Energy
- Oazer
- SPGA
- Inlandsbanan
- ...

Components Control

- ABB
- Hitachi
- GISAB
- …

Authorities

- Svenska kraftnät
- Energimyndigheten
- Vinnova
- Energimarknads-inspektionen
- MSB
- …

Consultants

- Sweco
- AFRY
- DNV
- Node pole
- …

Universities

- LTU
- UmU
- Gävle
- KTH
- …

Institutes

- RISE
- Swerim
- IVL
- SEI
- …

Networks

- Vätgas Sverige
- Energigas Sverige
- Energiforsk
- Energi-företagen
- …

Public sector

- Kommuner
- Regioner
- Näringslivs-bolag
- Handels-kammare
- …

Investors

- Polhem Infra
- AP
- …

Others

- Invest in Norrbotten
- Node Pole
- Business Sweden
- …

Figure 27. Some of the key stakeholders in northern Sweden, divided in traditional stakeholder groups.

Energy utilities

- Equinor
- Horisont Energi
- Varanger Kraft
- Statkraft

Distribution

- Aker Clean Hydrogen
- Everfuel (DK)
- Gasco
- Gen2 Energy
- GreenH
- Hexagon Purus
- Hyon
- IC Technology
- TechniqFMC (FR/US)
- Yara Clean Ammonia

Storage

- Equinor
- Everfuel
- IC Technology
- Gen2 Energy
- Hexagon Purus
- Horisont Energi
- Nel
- Statkraft
- Yara Clean Ammonia

Hydrogen generation

- Aker Clean Hydrogen
- BKK
- Gen2 Energy
- Glomfjord Hydrogen
- Hydrogen Havrand

Carbon capture

- Equinor
- Horizont Energi
- ZEG Power

Transport incl. shipping application

- ASKO
- Kongsberg Gruppen

Industry application

- Equinor
- Tizir
- Yara Clean Ammonia

Electrolysers

- Hydrogenics (CAN)
- Hystar
- Nel ASA

Figure 28. Some of the key stakeholders in Norway based on Business Sweden, 2022.

Energy utilities

- Fortum
- Fingrid
- Flexens
- EPV Energy
- Pori Energia
- Kotkan Energia Oy
- Tampereen Sähkölaitos Oy

Transport incl. shipping application

- Sisu Auto
- Linkker
- AGCO Power
- Wärtsilä

Industry application

- Neste
- SSAB
- UPM
- Stora Enso
- Metsä Group
- Terrafame
- Outokumpu
- Kemira
- Borealis Polymer
- Valmet
- Cargotec
- Solarfoods
- Ovako

Hydrogen generation

- Neste
- Woikoski
- Gasum
- Kemira
- Air Liquide Finland
- Hycamite
- Linde Gas
- P2X Solutions
- Q Power

Carbon capture

- Soletair Power

Electrolysers

- Convion

Distribution

- Ren-Gas
- Woikoski
- St1
- Gasgrid Finland
- Gasum

Storage

- Gasgrid Finland
- Baltic Connector
- Woikoski
- Gasum
- St1

Figure 29. Some of the key stakeholders in Finland based on Business Sweden, 2022.

Appendix 2. Summarising notes from interviews and discussions with the consortium

The following sections contain summarising notes from the interviews with the project consortium during the project period.

Organisation	Comment
ABB	As a technology provider, do not invest in projects financially. Involved in e.g. the Bothnia Link H2 project in Luleå, ABB's role in the realization of the Bothnia Link H2 project will be as electrical and automation contractor as well as providing digital and energy management solutions. ABB is currently in discussion with several industrial actors in the region where the role will be similar to the Bothnia Link H2 project.
Fertiberia Group	Hydrogen production, transportation for producing green Ammonia and green fertilizers, essential for food production, at present no fertilizer production in Sweden, 100% is imported. Planned hydrogen production in the Boden area connected with a pipeline to the ammonia plant and fertilizer complex next to the port in Luleå.
Fortum	Active in many large hydrogen projects where of two are planned in skellefteå and Luleå. Also several projects on the finnish side. Has a broad interest not only in the H2 itself but also combined with CO2 to produce chemicals, fuels and plastics
Fu-Gen Energi	Independent Power Producer, evaluating opportunities for downstream integration of renewable energy assets through hydrogen or hydrogen derivative production in order to facilitate a more holistic decarbonisation transition.
H2 Green Steel	Building a large-scale green steel plant in Boden with capacity of 2.5 M tons of steel in 2025 and 5 M Tons until 2030. Green hydrogen, produced from fossil free renewable energy will be an enabler for this.
Lhyfe	Lhyfe designs, builds, invests in, owns and operate renewable hydrogen production and distribution. Targeted range is 5 MW up to GW capacity. Interested in building value chain cooperations with transparent business models built on win/win. Cross investments are interesting in order to realise such partnerships.
Linde Gas	Linde is the leading gas company, produce and deliver gases including H2. Sister company Linde Engineering produces equipment and EPC projects. Different business models, could be a producer for a pipeline, but also develop own projects as well as in partnerships with the industry. Both as investor, technology provider and operator.
Liquid Wind	Electro fuel plant (P2X) plant i Örnsköldsvik. Hydrogen production and CO2 from Övik Energi. For marine applications.
LKAB	For Hybrit project pre-feed study is in start up phase. Systems analysis as well as capex and opex studies have been performed. Evaluating power supply.
Luleå Energi	LE is in a start up phase of establising operations in the hydrogen economy area. Main focus is residual heat. Participates in both Bothnia link and project in Luleå harbour.
Nordion Energi	The Nordic Hydrogen route, together with Gasgrid Finland https://nordichydrogenroute.com/sv/ An umbrella initiative aimed to develop a network of (cross-boarder) hydrogen pipelines in and around the Bothnia bay, but also in other Swedish regions. In parallel/under the initiative, regional "point-to-point" commercial pre-feasibility studies on-going.
Skellefteå Kraft	Infrastructure for fueling, heavy transport other projects not possible to disclose. Want to have a better picture of how the future infrastructure and need will look like.
SSAB	Partner in Hybrit. July 2021, SSAB rolled the first steel produced with HYBRIT technology, i.e. reduced with 100 percent hydrogen instead of coal and coke, with good results. 2022 Pilot for hydrogen storage up and unning i Port of Luleå.
St1	Feasibility for production of syntetic fuel. Sustainable aviation. Conrete investement (including steam reform H2) in relation to HVO plant. Refinery transformation ongoing.
Statkraft Hydrogen Sweden	Working with the steel and paper and chemical industry, supplies power. Several projects on both the Norwegian and Swedish side, transport of hydrogen on the Inlandsbana.
Svenska Kraftnät	Work with planning the grid for the fossil free north sweden the flexibility potential in northern Sweden, the target grid, looks very different with and without a hydrogen pipeline.
SWECO	Due diligence, 100-150 people working with hydrogen, technical consultants, working with feasibility studies.
Uniper	BothniaLink H2 project aims to create a H2 hub to decarbonize shipping, industry, and district heating in Luleå, by producing hydrogen and methanol.
Vattenfall	Power production is core business. Have been active within hydrogen for a long time and have competence mainly in production and storage of hydrogen and have a hydrogen strategy. Involved in many project not only in northern sweden.Hybrit one of them.
W3 Energy	Main activity is asset managment of wind farms specialized in cold climate. Manages a total of 1860MW which is app 18% of swedish wind establishment.
Wpd Offshore Sweden	Large scale offshore wind power developer, four large production projects in Sweden, production of H2 in three of them. 3GW project planned, offshore wind AND H2 production. Permitting stage. Timeline is 2030. Important milestone, has passed the municipal veto.

Figure 30. On-going activities and investments for some stakeholders in the region. Focusing on industrial stakeholders, LTU and RISE are not included in this overview.

Summarising notes from interviews

In the following sections, subjective standpoints and comments from interviews with the project partners in the spring of 2022 are listed. There are other opinions from other stakeholders that have not been lifted from the interviews. This appendix is not a consensus document.

All partners active in the area continuously learn and develop the area, why earlier expressed thoughts might change. See this part of the document as a frozen moment also as a base for future research regarding development paths.

On power production, distribution and market

- The high environmental goals in Sweden is an enabler, it is creating credibility for sustainable production in Sweden.
- Power supply and price is a competitive advantageous in the area of the Northern Sweden at this time. But, we will see this change and we will see more requests than power availability. In the future other countries will have more renewable energy as well. We must act on our advantage now!
- Availability of land for establishment of new renewable power production, e.g. wind power production is a limitation.
- Great potential in off-shore wind, 7-8 active applications in the Northern Gulf of Bothnia on the Swedish side.
- There is an identified potential to use power from SE2 to SE1, as well as from Finland.
- Large interest for renewable power production. For certain product categories green hydrogen is anticipated to be a competitive advantage.
- Big uncertainties with extremely volatile prices on electricity.
- When power supply is short there must be priorities which project should have access to power first.
- The technology is not fully tested nor units operations level or with the whole value chain in perspective.

On production and use of hydrogen

- Hydrogen is seen to be a good complement to the existing energy system.
- Which are the optimal production sites for hydrogen?
    - Mapping of industrial symbiosis is needed. Where, who, waste streams, needs etc. How do we use excess heat and oxygen from hydrogen production? Compare on-shore and off-shore options.
    - There is a great potential in producing hydrogen behind the meter (if possible) from a cost point of view, partly since the fee to Svenska Kraftnät is avoided.
    - Hydrogen production and storage can provide stabilizing services to the power grid. Hydrogen can be produced and stored when prices are low (and windmills otherwise should have been shut down). The hydrogen could then either be sold to the market or used for power production if that is competitive at high demand. Hydrogen producers can also contribute to frequency stabilization.
    - It is probably a good idea with distributed hydrogen production close to windmill parks if utilisation for power production is expected to be low.

- Green hydrogen is an important feed-stock for production of renewable fuels, chemicals, fertilizers etc.
- Other energy carriers than hydrogen (such as synthetic fuels, ammonia and methanol), must be compared.
- It is currently not profitable with electricity-hydrogen-electricity conversion when the power demand is at “normal” levels.

On pipelines

- Local pipeline networks could be an efficient way of transportation to customer.
- Some stakeholder expect that a pipeline will contribute not only to transportation of hydrogen but also with storage capacity on its own, combined with other large storage facilities.
- Pipeline is of special interest for industry using hydrogen as a resource for production of chemicals, materials, fuels etc. But storage capacity in pipeline or other storage facilities will help stabilizing the energy system. Infrastructure for gas and power must be planned in parallel.
- Some deem hydrogen infrastructure/pipelines is a requirement for the hydrogen market. Some have no opinion yet – or work today as if there will be no pipelines to be on the safe side.
- Some will start to build networks of hydrogen pipelines already before all market regulations are in place. They are willing to take the risk not to waste time.
- It would be a possible scenario that local distribution networks are developed and in the next stage. Just like the electric grid initially was developed connecting hydro power sites with industry and after that extended further.
- The connection to Finland is important, especially after 2035 when the power demand in northern Sweden is anticipated to be far higher than supply. Finland has plans expanding wind power production but have less demand in industry for hydrogen compared to northern Sweden.
- A pipeline could create synergies for other purposes e.g. oxygenation of seabeds in the Baltic sea.
- A pipeline network could be expected to have a positive impact also on development of municipalities along the pipeline. Hydrogen off-take hubs could attract new businesses in the region. It could be businesses using hydrogen for their production, e.g. production of fertilizers or renewable fuels, or establishment of stations for hydrogen as transportation fuels.
- The general view is that it is a good idea than one part (like Nordion Energi) take responsibility. However, some stake holders argue that a pipeline should be owned by the Swedish state.
- Several regional actors showed interest in building regional distribution networks that could be connected to the “national” pipeline network.
- Power TSO (Transmission system operator) and Gas TSO must cooperate. They should be given that mission from the government.
- Permit processes takes long time. This is also a geopolitical safety issue.
- Which are the optimal pipeline routes?

- Simulate hydrogen flow in pipelines.
- How to control the pipeline system?
- Ownership of pipeline infrastructure?
- How do we integrate flexibility and robustness in the infrastructure?
- How to measure quality and how to calculate/keep track of climate reduction?
- What will happen if we connect the hydrogen system to the one European with its huge demand?
- How to develop more local suppliers of components? Development of materials for electrolysers.

On hydrogen storage

- Storage of hydrogen is not well studied.
- Technology verification of large storage facilities is necessary.
- Map storage need relative to storage in pipeline, large customers, lack of wind for weeks etc.
- How to calculate backup coverage when many actors uses same pipelines and storage volumes?
- Development and testing of technology for hydrogen production, more research is needed.
- Production, storage, transportation in cold climate.

On regulations, policies and certification

- The general opinion among the stakeholders is that the Swedish government is not active enough. They must take a much more active role and actually activate and evaluate the national strategy suggested by the Swedish Energy Agency, November 2021. That would include facilitating permits, secure availability of land, policies etc.
- The hydrogen market that will result from pipeline networks must be available and with fair pricing for all companies including SMEs. Ownership of the infrastructure, national regulations and control of the market when it comes to tariffs etc is an extremely important area where a lot of work will be required and knowledge must be built.
- Certificates and standards help building markets for new products since they guarantee leveled playing fields with common rules for all actors on a market. But, it is also a very complex issue.
- It is challenging for companies in the process of transition into new products and markets to keep up with what is going on regarding national and/or international regulations. Existing industry must act according to existing laws for existing production at the same time as they are on a “transition journey” with new and changing regulations.
- Standards must be developed on an international level and it is crucial that make sure that our national interests and needs are being met. Today there are many examples that Swedish and EU targets mismatch.
- It might be necessary with regional standards and policies.

- Green certificates or CO_2 tax would improve market situation for green hydrogen and for sustainable products made there-off. Production costs are initially higher in new value chains due to small volumes produced and the first production asset built is always more expensive than those following. At the same time customers are on most markets not willing to pay a green premium. Hence, it is difficult to introduce new sustainable products and build a market. Financial support from government or public sector or risk sharing could help increasing speed to market for these products.
- Incentives must rather be long term than perfect in all details.
- Hydrogen market with regulated tariffs is expected, possible including green certificates.
- Some find the hydrogen regulations to easy having unexperienced stakeholders in mind.
- Time. It takes far too long to get permits for establishment or production along the entire value chain from wind power parks to production facilities, pipelines and power grids. There is more or less consensus on this point among the interviewed companies.
- Politicians must take lead, and set a plan. Regulations must be set. From the industries side it is a huge risk not knowing how and when regulations will change.
- Shortage of available land for establishments in attractive areas is an obstacle.
- Financial support from public sector is not ready.
- Technical regulations and guidelines for pipelines, hydrogen plants has to be developed.
- Differentiation of taxes for different actors
- The process for permits for establishments of wind power parks is challenging.

On risks and safety

- Safety must be a top priority. Handling risks related to the hydrogen economy is of high importance. Accidents would not only put lives at risk it would also severely impair the hydrogen brand and lowering social acceptance.
- Geopolitical security. The hydrogen network must be constructed so it is not exposed to forces aiming at impairing our energy system. An underground solution would be preferred for this reason according to some.
- Hydrogen production and utilisation is new for most stake holders so a lot of knowledge is missing. Not least do the rescue services need to regulate a certain operation.
- There must be national regulations regarding risk and safety. Myndigheten för samhällsskydd och beredskap (MSB) should be responsible. Now it is up to local rescue services to decide on this. So, there could be big regional differences. And this lack of coordination also make knowledge building and sharing more difficult.
- Some argue that it is unclear who is responsible for permits when it comes to safety.
- Regarding safety distances, best practise is missing which is an obstacle in permit processes.
- New equipment in new value chain has not been tested in large scale.

The municipality and social acceptance

- Social acceptance is low when the landscape and people's life are impacted by operations related to energy or industry operations. With increased activities in the area it could be anticipated that this will create worries and anxiety in the society with lower social acceptance as a consequence, especially so if energy prices start to rise as a consequence of industrial establishments.
- The impact on the environment will be important when constructing a pipeline network that covers large geographical areas. This will result in many processes for permits etc it will hence take very long time. Can the process be changed? Complaints from the society and municipalities has a huge impact on the permits process today. Too many levels of instances the complaints must pass. There is no cost involved if you want to complain. Can this be changed without lowering the safety and integrity of the legal system.
- The municipalities must be involved in the planning process from the beginning and they must see that there is an up-side for them. The unwillingness to accept windmill parks is an example where "municipal veto" and low social acceptance delays investments for many years and even prevent the totally.
- It is important that the society feel and believe that the new "hydrogen economy" is the future also for them.
- It is important that politicians and industry tell the "good story" and show how the local society can benefit from the development with development of local businesses and opportunities.
- Having large international companies capitalizing on the local environment with no positive effect on the local municipality lower social acceptance. the municipalities must for ex be paid for the poser produced in windmill parks.
- With large industry establishments a lot of resources will be needed, both during construction but also when in operation. How will societies be impacted by increased fly in/fly out?
- Build knowledge on how to build social acceptance

On knowledge and educational needs

- The hydrogen economy and infrastructure around it is new. This means that there is a lack of knowledge in all segments: society, industry, politicians, rescue services etc
- The systems perspective is very important. There is a lack in educated people with expertise and there is a need for further development of methods for systems analysis.
- Mapping of competencies. Who knows what and what competencies are missing?
  - To few with good knowledge about safety and risk, along the entire value chain.
  - General knowledge lift is needed in public sector, authorities and rescue services
  - Knowledge lift internally in companies as their operations changes in times of transition.
  - When industry operation changes and energy companies move towards chemicals production (hydrogen) also the municipality and its actors need to follow and adapt. New knowledge is needed where responsibility for permits is.
  - There is a lack of entrepreneurs and equipment manufacturers. As the hydrogen economy grows there will be a huge shortage on electrolysers with long delivery times as a consequence.

    - The process for permits could be faster if authorities and public sector had better knowledge
    - Many new sustainable products can be developed with hydrogen as an important feed stock. Green CO2 (and biogas) is a necessary building block in many of these. However, both of these are hard to find.
- For example, how do we create opportunities from the fact that energy demanding operations can be established “behind the meter”. Can the municipalities take lead? Create SME networks?

- We must learn from other gas grids like the gas grid in southern Sweden.

Appendix 3. Regulatory framework for use of oxygen

*This appendix is translated from the report "*Vätgasproduktion för ellagring efter elnätsnytta och affärsmodeller" *by RISE in Swedish. It focuses on a hydrogen refueling station but is to a large extent relevant for detached hydrogen production through electrolysis.*

Briefly about oxygen

Oxygen (O_2) is a by-product of electrolysis. For every kilogram of hydrogen gas 8 kg of oxygen is produced. At present, the normality is that oxygen is vented to the atmosphere without being used. Oxygen is non-toxic and is present in the atmosphere (about 21%) but in concentrated quantities there are some safety risks. Oxygen can be used, among other things, in several industrial processes and for healthcare treatments.

Oxygen-enriched environments - Oxygen is highly fire-sustaining, that is, it causes existing fires to burn more intensely (even explosively) and makes ignition more likely. Hair and clothes burn much more easily in oxygen-rich environments and oxygen even make it possible to ignite materials that do not usually burn in an ordinary atmosphere. A well-known and tragic example of the risks is Apollo 1, in which the atmosphere in the space capsule was intentionally pure oxygen. An electrical fault led to a fire that caused the deaths of all astronauts in the capsule.

Leakage of oxygen thus means a risk that hazardous environments are formed. Therefore, it is necessary that the environment in which the oxygen is stored is adapted accordingly. Often, oxygen is also stored at elevated pressure in a pressure vessel, which entails a certain risk when handling, but sometimes it is stored cooled in liquid form and then there is a risk of frostbite. Handling of oxygen is thus not completely harmless, especially if it is to be handled in together with other flammable substances such as hydrogen.

Regulations

There is a wide range of laws, regulations, recommendations, guidelines, and standards for how oxygen should be handled. Broadly speaking, these laws cover how the gas may be stored, handled, and transported. In this report, oxygen is only treated in its gaseous form, but in industry it is also common for oxygen to occur in cooled liquid form, then other rules apply. To know which rules, apply, you must first have a clear picture of how the oxygen is intended to be used. Therefore, in this report, only selected regulatory frameworks are covered.

Practices & Recommendations

Interview with emergency services

Fire engineer Erik Lyckebäck at the rescue service Östra Skaraborg was interviewed (24-Aug 2021) and answered questions about the handling of oxygen. Unlike flammable gases such as hydrogen, oxygen is only a fire-supporting gas, which means that the emergency services do not need to carry out permits for handling oxygen. However, the emergency services in Östra Skaraborg usually provide advice regarding the handling of oxygen tubes. Mainly it is about tubes that are to be used in healthcare or in welding. Large-scale handling of oxygen is not something that has occurred in the areas of the rescue service Östra Skaraborg, they believe that large stocks of oxygen occur rarely, in general. Even though oxygen is not a flammable gas in the sense of the law, the emergency services still recommend the utmost care and that the gas is practically considered a flammable gas from a safety point of view.

The rescue service Östra Skaraborg believes that the idea of utilizing oxygen from electrolysis is very interesting, but that it also brings new challenges. Experience of large-scale handling of oxygen is missing, but it is possible that other actors have experience. Working with permits is always more complicated and requires more time for new and non-standard projects like this. Risk analyzes must be issued specifically for the plant; it is not possible to rely on ”table-values”. In general, there is a lack of adapted regulations for electrolysis and hydrogen in mobility, which makes the work more difficult. For example, the original permit process for the hydrogen refueling station in Mariestad required a very long time before it was approved. According to the emergency services, adding a storage of oxygen to an existing hydrogen refueling station had also required that the old risk analyses for the hydrogen refueling station must be re-evaluated as oxygen affects the hydrogen fire risk.

For future permit processes to go as quickly and smoothly as possible, the emergency services suggest that they and MSB (Swedish Civil Contingencies Agency) are involved at the earliest possible stage. This also allows the permitting process to go faster.

Oxygen in operations - companies in Sweden

Two companies with operations in Sweden have been interviewed regarding how they work with oxygen in their operations. In addition to statutory requirements, companies choose to follow their own procedures/standards to ensure the highest possible safety. For example, a company states that they choose to treat the oxygen as if it were hydrogen or another flammable gas, even though it should not be considered as such within the meaning of the law. Another company says that they take the safety risks posed by oxygen very seriously. They state that the safety risks associated with oxygen are one of the reasons why they choose to ventilate the oxygen which stems from their electrolysis process.

When it comes to general advice on the handling of oxygen, Air Liquide tells the following on its website for oxygen (in Swedish). The advice applies mainly to those who intend to use the oxygen (for example, for welding or medical care) and is thus perhaps not as applicable to industrial use or the production of oxygen. In addition to obvious advice such as ”avoid fire”, there are suggestions on how oxygen can make oil, fats, clothing, and hair more flammable and should avoid contact with oxygen.

Regulatory framework

The following is not a complete list of regulations for the management of oxygen. This chapter mainly lists laws, regulations, and legal aspects. For the safe use of oxygen, current standards and best-practices must also be followed, which is only partially stated here.

Oxygen is not classified by MSB as flammable gas, but the practice of many companies is still to handle it as such, therefore some regulations for flammable gas are also listed. Within the regulations for flammable gas, there are also paragraphs on co-storage with other gases (such as oxygen). It is also worth noting that other countries may have different classifications and regulations for oxygen. In Germany, for example, there are much clearer regulations specifically for only oxygen such as BGV B7 - Sauerstoff (old version) (in German).

Authorities use different denotations and categories to characterize a substance and its properties. The following classifications are those used by MSB, AFS (Swedish Work Environment Authority) and ECHA (European Chemicals Agency).

MSB - Swedish Civil Contingencies Agency

- **Oxygen is a hazardous substance -** On RIB, a decision support for emergency services, (In Swedish) compressed oxygen is classified as a hazardous substance, ”Oxidizing (fire-supporting) gas”. This classification entails, inter alia, that there are specific regulations for how oxygen is to be transported on road vehicles and trains (ADR-S and RID-S).
- **Oxygen is not a flammable gas -** According to the MSB's definition of flammable gases, oxygen is not a flammable gas. Since oxygen does not in itself form a flammable gas mixture with air, it is not a flammable gas, other sources also substantiate this claim.
- **Oxygen is not a fire-reactive commodity -** Oxygen is also not considered a fire-reactive commodity according to an email conversation with MSB. As it has not been specified as such in special regulations issued by the MSB and is consequently not classified as a fire-reactive product. This is somewhat confusing as oxygen clearly falls under the general

(but non-legal) description of flammable goods that MSB uses. MSB states that the description may change slightly in the future.

AFS - Swedish Work Environment Authority

- **Oxygen handled with pressurized devices** – When handling oxygen, pressurized devices are very likely to be used. For the handling of pressurized devices, it is mainly the Swedish Work Environment Authority's regulations that apply.

ECHA – European Chemicals Agency

- **Oxygen is covered by the CLP Regulation** – the CLP Regulation is an international system for the classification of hazardous substances. Among other things, the CLP Regulation states which warning signs to use for a substance. The CLP regulation, among other things, states that pressurized oxygen is classified according to the ”Hazard Statement Code H270 (May cause or intensify fire; oxidizes)”. It also states that the warning signs for oxidizing substances and gas cylinders should be used.

Information box 1: Classification in accordance with the CLP regulation

Index Number	EC / List no.	CAS Number	International Chemical Identification
008-001-00-8	231-956-9	7782-44-7	Oxygen

Classification		Labelling			Specific Concentration limits, M-Factors, Acute Toxicity Estimates (ATE)	Notes
Hazard Class and Category Code(s)	Hazard Statement Code(s)	Hazard Statement Code(s)	Supplementary Hazard Statement Code(s)	Pictograms, Signal Word Code(s)		
Press. Gas				GHS03 GHS04 Dgr		Note U
Ox. Gas 1	H270	H270				

Signal Words	Pictograms
Danger	Flame over circle; Gas cylinder

Flame over circle Gas cylinder

Rescue work - Accidents

In cases an accident should occur at a hydrogen refueling station, it is the rescue service that will carry out the rescue work. The work of the rescue services can be simplified by shaping the production facility in accordance with rescue work routines. Although there are requirements for some adaptation to meet current regulations, it can also be beneficial to coordinate with the emergency services so that the work is further simplified.

When it comes to rescue work in potentially explosive environments, the regulation ”The Swedish National Rescue Department's regulations on explosive environments when handling flammable gases and liquids” applies, SRVFS 2004:7. The regulation also includes a handbook ”The Rescue Department's handbook on explosive environments when handling flammable gases and liquids”.

Seveso - Management of large quantities of hazardous substances,

The Seveso legislation may become relevant when large quantities of hazardous substances are managed. The Seveso Directive has been developed by the EU and legislated in Sweden as the *Seveso Legislation* under (1999:381). Seveso aims at preventing and limiting the consequences of serious chemical accidents. The legislation sets lower and higher requirement levels for various hazardous substances. If the requirement levels are exceeded, special measures must be introduced, such as the preparation of accident action programs. Both hydrogen and oxygen are covered by Seveso legislation and a summarizing rule applies which says how large quantities of certain substances can be stored together.

EIGA - European Industrial Gases Association

EIGA is a technology- and safety-oriented organisation consisting of a consortium of several European and non-European companies that produce gas for industry and healthcare. EIGA does not issue official standards but cooperates with organisations for standardization and regulations. EIGA has published several documents on the safe handling of oxygen. These are summarized in the table below.

Table: EIGA’s recommended reading for safe handling of oxygen

Code	Title
NL 79	The hazards of oxygen enriched atmospheres
TP 12	Fire hazards of oxygen enriched atmospheres
Doc 4	Fire Hazards of Oxygen and Oxygen Enriched Atmospheres
Doc 10	Reciprocating Compressors for Oxygen Service
Doc 13	Oxygen Pipeline and Piping Systems
Doc 27	Centrifugal Compressors for Oxygen Service
Doc 33	Cleaning of Equipment for Oxygen Service
Doc 154	Safe Location of Oxygen and Inert Gas Vents
Doc 200	The Safe Design, Manufacture, Installation, Operation and Maintenance of Valves Used in Liquid Oxygen and Cold Gaseous Oxygen Systems.
Info 15	Safety Principles of High-Pressure Oxygen Systems

SiS – Swedish Institute for Standards

SiS is an organisation that publishes Swedish standards for industry and private use. SiS has many standards that cover oxygen, but most are for specialized use of oxygen. A general list of standards covering oxygen does not make sense (SiS gives more than 600 hits on the keyword ”oxygen”). However, it is worth searching among SiS standards if the specific use of the oxygen is known.

Medical use

Special provisions apply to oxygen intended to be used as a medicine, so-called ”medical oxygen”. Permits for the manufacture and sale of medicines are issued by the Medical Products Agency. There are two specific standards for medical oxygen, ”Oxygen” and ”Oxygen (93 percent)”. The standards specify the degree of purity of oxygen and how it should be handled and manufactured. This means, among other things, that the standards are currently written in a way that says that oxygen from electrolysis is not allowed for medical use.

Swedish handbooks - There are several manuals and documents that are intended to help interpret rules and teach best practices. These are often issued by the same authorities that issue the regulations. The following is a list of some of the manuals that may be relevant and useful:

Title (Swedish)	Published by	Link
Hantering av brandfarlig gas för yrkesmässig verksamhet	MSB	Link
Tillstånd till hantering av brandfarliga gaser och vätskor	MSB	Link
Handbok för riskanalys	MSB (räddningsverket)	Link
Räddningsverkets handbok om explosionsfarlig miljö vid hantering av brandfarliga gaser och vätskor	MSB (räddningsverket)	Link
Tankstationer för metangasdrivna fordon, TSA 2020[92]	Energigas Sverige	Link
SEK Handbok 426 - Klassning av explosionsfarliga områden - Områden med explosiv gasatmosfär	Svensk Elstandard	Link

Laws and Regulations

Rules for the handling of oxygen are in a state of change. Many of the regulations from MSB or the Swedish Work Environment Authority that may apply to oxygen are relatively new (several are from 2020) but it is likely that new regulations specifically for hydrogen refueling stations will be published. Interest for the topic of supervision of hydrogen refueling stations has been expressed to MSB in the past.

Although oxygen does not fall directly under the definition of a flammable gas, hydrogen gas does. For flammable gases, for example, there are rules for how the gas should be stored together with other gases.

The following is a list of the regulations that may be relevant for the handling and road distribution of oxygen but also for flammable gases and pressurized devices. The list is relevant for oxygen in gaseous form since electrolysis only produces gaseous oxygen. That is, liquid hydrogen is treated. Nor is the list relevant for distribution of oxygen via train because other regulations apply. Authors have also not included building regulations such as the Swedish National Board of Housing, Building and Planning's building regulations, BBR. These rules regulate, among other things, fire safety and evacuation routes in buildings.

Laws and regulations for oxygen (Swedish)

Classification	Title (Swedish)	Type	Published	Altered by
SFS (2010:2011)	Lag (2010:2011) om brandfarliga och explosiva varor	Lag	**2010-07-11**	SFS (2020:903)
SFS (1999:381)	Lag (1999:381) om åtgärder för att förebygga och begränsa följderna av allvarliga kemikalieolyckor	Lag	**1999-05-27**	SFS (2015:233)
SFS (2010:1075)	Förordning (2010:1075) om brandfarliga och explosiva varor	Förordning	**2010-07-15**	SFS (2020:790)
SFS (2015:236)	Förordning (2015:236) om åtgärder för att förebygga och begränsa följderna av allvarliga kemikalieolyckor	Förordning	**2015-04-23**	SFS (2018:1847)
SRVFS 2004:7	Föreskrifter om explosionsfarlig miljö vid hantering av brandfarliga gaser och vätskor	Föreskrift	**2004-03-17**	
MSBFS 2010:4	Föreskrifter om vilka varor som ska anses utgöra brandfarliga eller explosiva varor	Föreskrift	**2010-09-01**	MSFBS 2018:12
MSFBS 2011:3	Föreskrifter om transportabla tryckbärande anordningar	Föreskrift	**2011-06-30**	
MSBFS 2013:3	Föreskrifter om tillstånd till hantering av brandfarliga gaser och vätskor	Föreskrift	**2013-10-01**	
MSBFS 2015:8	Föreskrifter om åtgärder för att förebygga och begränsa följderna av allvarliga kemikalieolyckor	Föreskrift	**2015-06-01**	
MSBFS 2020:1	Föreskrifter om hantering av brandfarlig gas eller brandfarliga aerosoler	Föreskrift	**2021-08-01**	
MSBFS 2020:9	Föreskrifter om transport av farligt gods på väg och terräng (ADR-S)	Föreskrift	**2020-01-01**	
AFS 2006:8	Provning med över- eller undertryck (AFS 2006:8), föreskrifter	Föreskrift	**2007-01-15**	AFS 2011:5 AFS 2014:34 AFS 2020:8
AFS 2016:1	Tryckbärande anordningar (AFS 2016:1), föreskrifter	Föreskrift	**2016-05-09**	
AFS 2017:3	Användning och kontroll av trycksatta anordningar (AFS 2017:3), föreskrifter	Föreskrift	**2017-07-07**	AFS 2019:1 AFS 2020:10

Appendix 4. Demand data

NEW TABLE WITH SEPARATED HYDROGEN AND OTHER MOLECULES												
NORRBOTTEN	Present			2030			2040			2050		
Demands in MWh/y	Hydrogen	Other molecules	Electricity	Hydrogen	Other molecules	Electricity	Hydrogen	)ther molecule	Electricity	Hydrogen	Other molecules	Electricity
Boden	-	765 819	441 137	7 840 000	674 725	3 304 268	11 200 000	639 082	4 546 862	11 200 000	625 619	4 581 242
Gällivare	-	1 698 939	1 857 559	7 148 936	970 426	4 072 818	13 481 481	827 038	8 754 096	11 670 229	745 701	9 367 175
Kiruna	-	2 125 432	1 809 650	4 051 064	801 101	1 982 235	14 518 519	722 385	3 083 199	27 529 771	681 915	6 585 326
Luleå	-	12 315 193	1 468 508	2 240 000	3 871 640	5 137 716	2 240 000	3 796 983	6 482 157	2 240 000	3 807 096	6 640 465
Rest of Norrbotten	-	9 093 493	2 766 164	-	8 719 510	3 179 559	-	9 024 809	3 567 084	-	9 874 397	4 022 054
SUM NORRBOTTEN	**-**	**25 998 876**	**8 343 018**	**21 280 000**	**15 037 401**	**17 676 596**	**41 440 000**	**15 010 297**	**26 433 398**	**52 640 000**	**15 734 728**	**31 196 261**
		34 341 894			**53 993 998**			**82 883 695**			**99 570 990**	
VÄSTERBOTTEN	Present			2030			2040			2050		
Demands in MWh/y	Hydrogen	Other molecules	Electricity	Hydrogen	Other molecules	Electricity	Hydrogen	)ther molecule	Electricity	Hydrogen	Other molecules	Electricity
Skellefteå	-	2 269 217	1 566 871	-	1 953 813	4 748 426	-	1 811 494	4 865 875	-	1 738 409	4 957 681
Norsjö	-	104 379	89 546	-	71 675	106 062	-	55 223	116 559	-	45 273	124 648
Malå	-	196 551	47 994	-	160 827	64 854	-	144 626	59 772	-	136 233	65 841
SUM VÄSTERBOTTEN SE1	**-**	**2 570 147**	**1 704 411**	**-**	**2 186 315**	**4 919 342**	**-**	**2 011 343**	**5 042 206**	**-**	**1 919 915**	**5 148 171**
		4 274 558			**7 105 658**			**7 053 549**			**7 068 086**	
	I have no hydrogen figures for the Skellefteå companies, see the separate Skellefteå sheet. We need figures from RISE. (Kjell)											
SE1	Present			2030			2040			2050		
Demands in MWh/y	Hydrogen	Other molecules	Electricity	Hydrogen	Other molecules	Electricity	Hydrogen	)ther molecule	Electricity	Hydrogen	Other molecules	Electricity
SUM SE1	-	28 569 023	########	21 280 000	17 223 716	22 595 939	41 440 000	17 021 640	31 475 604	52 640 000	17 654 643	36 344 432
		38 616 452			**61 099 655**			**89 937 244**			**106 639 075**	

NORRBOTTEN	[MWh]	Present		2030		2040		2050	
		Molecules	Electricity	Molecules	Electricity	Molecules	Electricity	Molecules	Electricity
Boden	Separated industries	-	-	7 840 000	2 800 000	11 200 000	4 000 000	11 200 000	4 000 000
	Remaing industry and construction	26 503	13 557	27 828	14 235	29 153	29 153	30 478	30 478
	Transports	246 447	65 319	129 385	109 659	67 773	133 463	28 341	149 051
	Other	492 869	362 261	517 512	380 374	542 156	398 487	566 799	416 600
Gällivare	Separated industries	430 000	925 000	7 148 936	2 978 723	13 481 481	7 976 190	11 670 229	8 527 273
	Remaing industry and construction	359 340	741 405	377 307	778 475	395 274	395 274	413 241	413 241
	Transports	689 448	21 046	361 960	137 006	189 598	195 513	79 287	231 037
	Other	220 151	170 108	231 159	178 613	242 166	187 119	253 174	195 624
Kiruna	Separated industries	1 150 000	1 200 000	4 051 064	1 271 277	14 518 519	2 273 810	27 529 771	5 722 727
	Remaing industry and construction	310 915	281 338	326 461	295 405	342 007	342 007	357 552	357 552
	Transports	424 958	62 837	223 103	136 805	116 863	175 360	48 870	199 750
	Other	239 559	265 475	251 537	278 749	263 515	292 023	275 493	305 296
Luleå	Separated industries	8 156 970	344 000	2 240 000	3 800 000	2 240 000	3 800 000	2 240 000	3 800 000
	Remaing industry and construction	1 230 800	131 050	1 292 340	137 603	1 353 880	1 353 880	1 415 420	1 415 420
	Transports	941 894	2 939	494 494	160 068	259 021	238 706	108 318	285 948
	Other	1 985 529	990 519	2 084 805	1 040 045	2 184 082	1 089 571	2 283 358	1 139 097
BD remaining part	Remaing industry and construction	5 893 518	1 682 004	6 188 194	1 766 104	6 807 013	1 942 715	7 828 065	2 234 122
	Transports	1 578 396	22 658	828 658	298 877	434 059	456 717	181 516	567 205
	Other	1 621 579	1 061 502	1 702 658	1 114 577	1 783 737	1 167 652	1 864 816	1 220 727
SUM		**25 998 876**	**8 343 018**	**36 317 401**	**17 676 596**	**56 450 297**	**26 447 639**	**68 374 728**	**31 211 149**

VÄSTERBOTTEN SE1		Present		2030		2040		2050	
	[MWh]	Molecules	Electricity	Molecules	Electricity	Molecules	Electricity	Molecules	Electricity
Skellefteå	Specified industries	500 000	500 000	500 000	3 500 000	500 000	3 500 000	500 000	3 500 000
	Remaing industry and construction	375 702	377 814	394 487	396 705	413 272	413 272	432 057	432 057
	Transports	769 266	37 275	403 865	167 350	211 548	233 319	88 466	273 646
	The rest	624 249	651 782	655 461	684 371	686 674	716 960	717 886	749 549
	SUM	**2 269 217**	**1 566 871**	**1 953 813**	**4 748 426**	**1 811 494**	**4 863 551**	**1 738 409**	**4 955 253**
Norsjö	Industry and construction	8 357	44 738	8 775	46 975	9 193	9 193	9 611	9 611
	Transports	72 235	409	37 923	12 469	19 865	18 509	8 307	22 141
	The rest	23 787	44 399	24 976	46 619	26 166	48 839	27 355	51 059
	SUM	**104 379**	**89 546**	**71 675**	**106 062**	**55 223**	**76 540**	**45 273**	**82 810**
Malå	Industry and construction	3 536	16 911	3 713	17 757	3 890	3 890	4 066	4 066
	Transports	86 764	122	45 551	14 589	23 860	21 825	9 978	26 170
	The rest	106 251	30 961	111 564	32 509	116 876	34 057	122 189	35 605
	SUM	**196 551**	**47 994**	**160 827**	**64 854**	**144 626**	**59 772**	**136 233**	**65 841**
	SUM ALL THREE MUNICIPALITIES	**2 570 147**	**1 704 411**	**2 186 315**	**4 919 342**	**2 011 343**	**4 999 864**	**1 919 915**	**5 103 904**

Appendix 5. Planned wind power production (including current production)

Location	Estimated prod 2030 [GWh/y]	Estimated prod 2040 [GWh/y]
Vindeln	1386	1386
Robertsfors	548	548
Norsjö	185	185
Malå	442	442
Umeå	571	571
Skellefteå	3032	3032
Arvidsjaur	0	37
Arjeplog	80	80
Jokkmokk	1	526
Överkalix	547	547
Kalix	43	10989
Övertorneå	265	265
Pajala	1142	1142
Gällivare	1357	6300
Älvsbyn	0	0
Luleå	10	10
Piteå	8827	12897
Boden	0	1055
Haparanda	22	725
Kiruna	6	6
Alajärvi	552	552
Alavieska	466	466
Alavo	2	2
Enontekis	34	34
Evijärvi	0	0
Haapajärvi	773	773
Haapavesi	3645	3645
Karlö	107	107
Halso	1502	1502
Hyrynsalmi	616	616
Ijo	5973	5973
Ilmola	182	182
Enare	0	0
Storå	481	481
Storkyro	245	245
Kajana	5105	5105
Kalajoki	2403	2403
Kannus	1544	1544
Bötom	1533	1533
Kaskö	0	0
Kauhajoki	1122	1122
Kauhava	190	190
Kaustby	0	0
Kemi	135	135
Keminmaa	0	0
Kempele	0	0
Kittilä	156	156
Karleby	2688	2688
Kolari	0	0
Korsnäs	4400	4400
Kristinestad	1994	1994
Kronoby	0	0
Kuhmo	0	0
Kuortane	1134	1134
Kurikka	1423	1423
Kuusamo	1306	1306
Kärsämäki	2851	2851
Kemijärvi	297	297
Laihela	276	276
Lappajärvi	172	172

Location	Estimated prod 2030 [GWh/y]	Estimated prod 2040 [GWh/y]
Lappo	77	77
Lestijärvi	1395	1395
Limingo	365	365
Lumijoki	25	25
Larsmo	3	3
Malax	776	776
Merijärvi	83	83
Muhos	546	546
Muonio	9	9
Korsholm	392	392
Nivala	138	138
Närpes	3241	3241
Oulainen	537	537
Uleåborg	10875	10875
Paltamo	1533	1533
Pelkosenniemi	0	0
Perho	1674	1674
Jakobstad	7665	7665
Pedersöre	1478	1478
Posio	451	451
Pudasjärvi	1594	1594
Puolanka	1533	1533
Pyhäjoki	1858	1858
Pyhäjärvi	5568	5568
Pyhäntä	2606	2606
Brahestad	3851	3851
Ranua	0	0
Reisjärvi	0	0
Ristijärvi	0	0
Rovaniemi	607	607
Salla	411	411
Savukoski	0	0
Seinäjoki	25	25
Sievi	285	285
Siikajoki	1389	1389
Simo	1833	1833
Sodankylä	83	83
Soini	1619	1619
Sotkamo	0	0
Suomussalmi	120	120
Vaala	451	451
Siikalatva	3940	3940
Taivalkoski	0	0
Tervola	365	365
Östermark	432	432
Toholampi	607	607
Torneå	3931	3931
Pello	313	313
Tyrnävä	0	0
Utajärvi	2266	2266
Utsjoki	0	0
Nykarleby	1475	1475
Vasa	172	172
Vetil	92	92
Vindala	0	0
Vörå	877	877
Övertorneå	1741	1741
Ylivieska	809	809
Etseri	0	0
SUM	**133884**	**156163**

Appendix 6. Details of the preliminary cost calculations for Scenario B

Summary

Here is a numerical table summarizing all costs of the infrastructure in scenario B:

			€/kg	€/MWh			€/kg	€/MWh
		low	2.526	75.78				
H2 production		mean	2.907	87.21				
		high	3.098	92.94				
H2 storage (incl. compression)			0.990	29.74				
		low	0.033	1.00		low	0.079	2.37
H2 transmission (pipes)	method 1	med	0.036	1.09	method 2	base	0.093	2.79
		high	0.044	1.32		high	0.125	3.76
		low	0.007	0.21		low	0.006	0.17
H2 transmission (recomp. stations)	method 1	med	0.010	0.31	method 2	base	0.007	0.20
		high	0.016	0.49		high	0.009	0.27
		low	0.040	1.21		low	0.085	2.54
H2 transmission (subtotal)	method 1	med	0.047	1.40	method 2	base	0.100	2.99
		high	0.060	1.81		high	0.135	4.04
		low	3.556	123.89		low	3.601	125.22
total infrastructure cost	method 1	med	4.135	124.08	method 2	base	3.997	125.67
		high	4.148	124.49		high	4.223	126.72

The details for the estimations of storage and transmission costs are described in the following subsections.

Hydrogen storage

The following table shows the results of the cost estimation for hydrogen storage, starting from the local hydrogen production at each station:

		Gällivare	Boden	Tornio	Oulu
local production	TWh/y	5	18.4	6	21
	tH2/y	150000	552000	180000	630000
storage capacity	tH2	30000	110400	36000	126000
	m3	1785714	6571429	2142857	7500000
capex	MEUR	1661.55	6114.504	1993.86	6978.51
annual capex	MEUR/y	108.09	397.76	129.70	453.96
annual non-energy opex	MEUR/y	33.23	122.29	39.88	139.57
annual energy opex	MEUR/y	14.00	51.52	16.80	58.80
total	MEUR/y	155.32	571.57	186.38	652.33
	EUR/MWh	2.95	10.86	3.54	12.39
	EUR/kg	0.098	0.362	0.118	0.413

Hydrogen transmission (pipes)

Here is a summary of the technical parameters of the pipeline segments:

		ou-to	gä-ki & to-bo	bo-gä
pipe capacity	TWh/y	25	30	35
H2 mass flow	kg/s	23.78	28.54	33.30
diameter	m	0.58	0.64	0.69
	in	22.8	25.2	27.2
length	km	125	203	162

The cost parameters used in Method 1 are illustrated in the following figure taken from (EHB, 2022) – small pipe = 20 inch diameter, medium = 36 inch, high = 48 inch.

Cost parameter		Low	Medium	High	Unit
Pipeline Capex, new	Small	1.4	1.5	1.8	M€/km
	Medium	2.0	2.2	2.7	
	Large	2.5	2.8	3.4	
	Offshore Medium	3.4	3.7	4.6	
	Offshore Large	4.3	4.8	5.8	
Pipeline operating & maintenance costs		0.8	0.9	1.0	€/year as % of Capex
Weighted average cost of capital		5.0			%
Depreciation period pipelines		40			Years

Applying these parameters, the estimated costs of the pipes according to Method 1 are calculated in the following table:

			low	med	high
capex		MEUR	783	848	1028
annual capex		MEUR/y	45.64	49.44	59.90
annual opex		MEUR/y	7.13	7.73	9.36
total		MEUR/y	52.77	57.17	69.26
		EUR/MWh	1.00	1.09	1.32
		EUR/kg	0.033	0.036	0.044

The cost parameters used in Method 2 are illustrated in the following figure taken from (Element Energy Ltd, 2018) – in addition to an 8% WACC and a depreciation period of 50 years.

Summary data

- The capital cost of pipeline[1] and compressors[1] are calculated as

$$Pipeline\ cost\ (£m/km) = 0.064\ x\ Pipeline\ diameter\ (inches) - 0.2799$$

$$Compressor\ cost\ (£m) = 0.3114\ x\ Compressor\ size\ (MW) + 1.3869$$

- The annual fixed opex is calculated as 5% and 15% of pipeline and compressor capital cost respectively

- To understand the sensitivity of the Transmission pipeline costs on the overall conversion an upper and lower cost scenario is provided.
- The Lower / Upper capex cost will be -15% / +35% of the Base value.

Applying these parameters, the estimated costs of the pipes according to Method 2 are calculated in the following table:

			low	base	high
capex		M£ (2018)		655	
		MEUR		1113	
annual capex		MEUR/y		91.00	
annual opex		MEUR/y		55.66	
total		MEUR/y		146.66	
		EUR/MWh	2.37	2.79	3.76
		EUR/kg	0.079	0.093	0.125

hydrogen transmission (recompressing stations)

Here is a summary of the mass flow rates leaving the recompression stations and the required compression power:

		TWh/y	kg/s	MWe
Boden	leaving to Gällivare	34.2	32.53425	11.80993
Oulu	leaving to Tornio	23.74	22.58371	8.197888

The cost parameters used in Method 1 are illustrated in the following figure taken from (EHB, 2022).

Cost parameter	Low	Medium	High	Unit
Compressor station Capex	2.2	3.4	6.7	M€/MW$_e$
Electricity price	40	60	80	€/MWh
Compressor operating & maintenance costs	1.7	1.7	1.7	€/year as % of Capex
Weighted average cost of capital		5.0		%
Depreciation period compressors		25		Years

Applying these parameters, the estimated costs of the recompression stations according to Method 1 are calculated in the following table:

				Boden			Oulu	
			low	med	high	low	med	high
capex		MEUR	25.98	40.15	79.13	18.04	27.87	54.93
annual capex		MEUR/y	1.84	2.85	5.61	1.28	1.98	3.90
ann non-energy opex		MEUR/y	0.44	0.68	1.35	0.31	0.47	0.93
ann energy opex		MEUR/y	4.14	6.21	8.28	2.87	4.31	5.75
total		MEUR/y	6.42	9.74	15.24	4.46	6.76	10.58
		EUR/MWh	0.12	0.19	0.29	0.08	0.13	0.20
		EUR/kg	0.004	0.006	0.010	0.003	0.004	0.007

The cost parameters used in Method 2 are illustrated in the following figure taken from (Element Energy Ltd, 2018) – in addition to an 8% WACC and a depreciation period of 15 years.

Summary data

- The capital cost of pipeline[1] and compressors[1] are calculated as

$$Pipeline\ cost\ (£m/km) = 0.064\ x\ Pipeline\ diameter\ (inches) - 0.2799$$

$$Compressor\ cost\ (£m) = 0.3114\ x\ Compressor\ size\ (MW) + 1.3869$$

- The annual fixed opex is calculated as 5% and 15% of pipeline and compressor capital cost respectively

- To understand the sensitivity of the Transmission pipeline costs on the overall conversion an upper and lower cost scenario is provided.
- The Lower / Upper capex cost will be -15% / +35% of the Base value.

Applying these parameters, the estimated costs of the recompression stations according to Method 2 are calculated in the following table:

			Boden			Oulu	
		low	base	high	low	base	high
capex	M£ (2018)		5.06			3.94	
	MEUR		8.60			6.69	
annual capex	MEUR/y		1.00			0.78	
ann non-energy opex	MEUR/y		1.29			0.59	
ann energy opex	MEUR/y		4.14			2.87	
total	MEUR/y		6.43			4.24	
	EUR/MWh	0.10	0.12	0.16	0.07	0.08	0.11
	EUR/kg	0.003	0.004	0.005	0.002	0.003	0.004

Appendix 7. Main conclusions from the IVA report “Vätgas och dess roll i elsystemet”

The complete report can be downloaded from the IVA site or from this link:

> https://www.iva.se/globalassets/bilder/projekt/vatgasprojektet/202205-iva-vatgasprojektet-syntesrapport-n.pdf (IVA, 2022)

The report's focus is on a discussion and analysis of the role of hydrogen in the time perspective up to the year 2030, but with a view to the year 2045 when Sweden will have net zero emissions of greenhouse gases. In this context, we have made a number of observations that are summarized below.

A general remark is that hydrogen is mainly expected to be used as a feedstock in industrial processes and as a fuel for heavy transport where direct electrification becomes too costly or technically difficult. To only use hydrogen to store renewable power with the aim to produce power again has an exceptionally low efficiency and should only be used in cases when the efficiency is secondary to other requirements (see below).

1) Significant challenge to produce the electricity that will be needed for electrification of industry and transport

If all existing and new hydrogen is to be produced by water electrolysis, it requires very large amounts of electricity. An overall challenge for creating a large hydrogen market is that the electrification of industry and the transport sectors is expected to result in a doubling of the electricity demand by 2045. The increased electricity demand can in the coming ten years only be met by intermittent power production, mainly via wind turbines, which in turn poses challenges in balancing the electricity system. In the longer term, other options might become available.

2) Challenges to obtain electricity are mainly of a non-technical nature in the form of long permit processes and lack of social acceptance.

The expansion of power production for electrification, including for hydrogen production, presupposes local acceptance and approval by the local municipalities - not least for wind power and new transmission lines. This requires better collaboration with local communities, while at the same time giving the municipalities financial incentives to speed up the expansion. This is especially true in southern Sweden, where the population density is highest, and where the need for new electricity production is the largest. It must also be ensured that Svenska Kraftnät (the only TSO in Sweden) can expand the network at a pace that can meet the market's needs.

3) Indirect electrification with hydrogen provides opportunities despite lower efficiency than direct electrification

Electricity is the most refined form of energy and should be used as efficiently as possible. Production of hydrogen with electricity entails a loss of high-value energy by about 30-40 percent while the losses with direct electrification can be much lower. Electricity should therefore be used directly wherever possible. Electrolysis-based hydrogen may still play a role where direct electrification is not possible. The hydrogen gas can be stored, also on a large scale, which means that it can contribute to flexibility in electricity use and thus fits well into a power system with large amounts of intermittent power production, and especially from wind power. The hydrogen gas can thus increase the value of the intermittent power production and reduce the losses in the energy system. Hydrogen storage is a complement to energy storage with batteries. Batteries are better suited for shorter variations to, for example, balance diurnal variations in electricity use or variations from solar cell output, while hydrogen stocks can balance the variation in wind power over a couple of weeks.

4) Hydrogen can contribute to the refining of Swedish raw materials and yield large reductions in greenhouse gas emissions.

Sweden's prosperity is largely based on the refinement of Swedish natural resources (ore and forest) with the help of electricity from hydropower and nuclear power. Further electrification is a bridge into a fossil-free society. Hydrogen produced with fossil-free electricity is an opportunity to restructure industries where hydrogen can be used as a feedstock for the production of carbon neutral materials, such as steel and polymers of various kinds. Combustion of hydrogen gas can be justified for high-temperature processes where the heat that is needed is easier to create from hydrogen combustion than directly from electricity. What in practice determines when hydrogen will be used is what the cost will be for a hydrogen solution compared to other carbon dioxide-free alternatives such as direct electrification, switching to bio-raw material / fuel or carbon capture and storage (CCS).

5) There is great uncertainty about how large the demand for hydrogen will actually be.

How large the demand for hydrogen will be depends on how the alternatives are developed. All assessments of future hydrogen needs are therefore subject to great uncertainty. In Sweden, demand is primarily driven by the projects planned in the steel and automotive industries with strong value chains ”from mine to truck”.

For the petrochemical and refinery industries, the uncertainties are even greater regarding how large the hydrogen demand may be as it depends on the supply of biomass, which products may be in demand and the degree of electrification of the processes and transports, and whether CCS will be an alternative. Recently, a couple of projects have been presented where hydrogen will be used for the production of aviation fuel. Aviation is an example of a sector where direct electrification can not be expected over the foreseeable future other than for smaller short-haul flights.

A rough estimate - based on the projects presented so far - is that by 2030 the demand for hydrogen will increase by about 20-25 TWh_{H2}. The demand until 2050 will increase significantly, probably by a factor 2-3.

6) Hydrogen gas can be produced from natural gas, biomass or renewable electricity - all of which can be used for the foreseeable future.

Today, virtually all hydrogen is produced via steam reforming of fossil fuels, such as natural gas or naphtha. The hope is that all hydrogen in the future will be produced from fossil-free electricity, but this will be difficult to achieve at the pace needed to achieve a rapid reduction in greenhouse gas emissions. Hydrogen can also be produced by gasifying biomass or from biogas. During a transitional period, it may be necessary to use fossil-based hydrogen where the carbon content is separated and stored, so-called ”blue hydrogen”. Hydrogen gas can also be produced via pyrolysis of natural gas, which gives a fine carbon powder (carbon black) as a by-product. The advantage is that final storage of a carbon powder is much easier and cheaper than storage of carbon dioxide.

There is expected to be increased competition for both electricity and biomass as the pace of the transition increases. Therefore, all three ways to produce hydrogen (electrolysis, from biomass, blue hydrogen) may be realised depending on local conditions, but blue hydrogen can make a very rapid conversion possible. Especially for the chemical and refinery industries on the West Coast where the power grid is weak, blue hydrogen may be an alternative.

7) The industry is driving the development of new technology for hydrogen-based processes.

Until 2030, we estimate that it is primarily the iron and steel industry that will drive the development of hydrogen technology, even though a hydrogen-based aviation fuel project has recently been presented. Other investments will probably mainly consist of spin-off effects of industrial projects, or an interest in maintaining and developing values in existing facilities, such as the natural gas infrastructure, gas turbines or a cogeneration system.

8) Investments are driven by the possibility of a premium market for fossil-free materials

The added value will be higher for ”hydrogen to material” than for hydrogen as an energy product. There are segments or niches where it is already possible to get paid more for a climate-neutral alternative than for the corresponding fossil alternative. Many manufacturers of consumer products and vehicles have set goals for climate neutrality, they need to change their entire value chain, including buying climate-neutral materials for their products, which helps drive demand for hydrogen.

9) The by-products from water electrolysis - oxygen and heat, can make a contribution on the margin but will not build the business.

All resources should be used as efficiently as possible. This includes the oxygen that is formed, and the heat that is generated in an electrolyser. Notice, that 8 times as much oxygen as hydrogen is formed by electrolysis of water. Even if there is a market for oxygen, the available volumes will be so large locally that prices are likely to drop so low that only smaller quantities can be utilised economically. The waste heat is high enough to be used for local heating or in a district heating system. What benefit it can do is governed by the location of the electrolyser and pricing of the heat.

10) Hydrogen-based E-fuels or materials can become competitive even if they are energy-intensive to produce

E-materials and E-fuels can be produced with carbon dioxide as a carbon source, together with hydrogen gas. The process is energy-intensive but can be an interesting alternative depending on local conditions for hydrogen production and which carbon dioxide streams are available. In order for E-fuels to be considered renewable, the carbon dioxide must come either from biomass or from carbon dioxide that is captured directly from the air.

A less energy-intensive way of producing fuels or building blocks for the chemical industry than starting from carbon dioxide is to gasify the biomass (for example forest waste) into a syngas (carbon monoxide, carbon dioxide, hydrogen). Then renewable hydrogen is added to the syngas, so that all the carbon in the constituent biomass can be converted into high-quality products. The energy stored in these fuels and materials comes to just over 50 percent from electricity and the rest comes from biomass.

11) It is unlikely that electricity will be stored as hydrogen for new electricity production.

Hydrogen can be used to produce electricity, in a fuel cell or in a hydrogen-fired turbine. Since there are losses both in the production of hydrogen, and in the production of electricity from the hydrogen, the system efficiency is about 30 percent. That is, the losses amount to 70 percent.

Making electricity from hydrogen can still be an option for short periods of time when other flexibility is not enough and the willingness to pay during these hours is high. However, it is unlikely that this will be profitable before 2030. From a systems perspective, studies show that it can be cost-effective by 2045, when the goal is that greenhouse gas emissions should be zero or close to zero. In that case, it will probably also require an electricity market solution that rewards this, ie some form of power market. Industry could also in some cases contribute to such electricity production. In cases where an industry for other reasons invests in a hydrogen process and a larger hydrogen storage facility, electricity can be stored and re-produced at cost parity with the older oil fired, condensing power plants that are currently used as power reserves in the electricity system.

12) Hydrogen production can contribute to reduced price volatility in the electricity market.

Hydrogen storage can enable better utilisation of variable electricity production. The industrial players that invest in hydrogen therefore also analyze the possibilities of taking advantage of the variation in electricity prices. This presupposes that they invest in some overcapacity in the electrolysers and supplement the plant with a hydrogen storage. This results in a higher investment cost but can be justified by the possibility of avoiding high electricity prices and redundancy in the hydrogen supply to the process. This in turn creates increased price elasticity in the electricity market.

13) The electricity system in southern Sweden at present limits the possibilities for a change in existing industry.

Hydrogen is used in large quantities in the production of fuels and certain chemicals. The oil refineries today produce their own hydrogen from internal feedstocks (naphta), but depending on price and needs, the need is supplemented with production from imported fossil gas. With increased production of biofuels, the need for hydrogen will increase sharply. For the chemical industry that is connected to a steam cracker plant that uses ethane, LPG (propane, butane) or naphtha as a raw material, a large excess of hydrogen is generated. This surplus is currently used to cover the heating needs of the processes, while at the same time limiting carbon dioxide emissions. Here, increased use of hydrogen can further reduce these industries' carbon dioxide emissions.

If refineries and the chemical industry are to become climate neutral with the help of hydrogen from electrolysis, it will require very large amounts of electricity in southern Sweden, which the electricity system today cannot supply. The alternatives are to supply existing processes with CCS, or import hydrogen, for example as ammonia. Imports of hydrogen as gas, or ammonia, would give refineries and the chemical industry an opportunity to create independence to satisfy their hydrogen and energy needs.

14) Pipeline infrastructure is cost-effective for transporting hydrogen.

Pipeline infrastructure is a cost-effective way of transporting hydrogen even at relatively small volumes. Therefore, it may be more cost-effective to transport hydrogen from electrolysis plants located near the power plant than to transport the electricity to an electrolysis plant near the hydrogen user. Therefore, a hydrogen pipeline infrastructure is likely to be built to meet the needs of industry. Initially, it is likely that local networks will be built, followed by regional networks that connect the local ones and after 2030, possibly a national (and international) backbone network. Such an infrastructure also enables de-bottlenecking of the electricity grid by optimizing the location of electrolysis plants in relation to available power production and electricity grid capacity.

15) There is currently no overall picture of how current regulations affect the development of a hydrogen market.

A number of relatively general surveys have been made of the regulations that apply to hydrogen (production, distribution, storage and use), carried out by authorities, organisations and consulting companies. However, there is no complete survey of current regulations. Such a survey is necessary in order to be able to make adjustments to current regulations as well as additions to the same in order to achieve the goals regarding hydrogen.

16) It might be a problem that electricity-based hydrogen must be produced from new, additional renewable electricity in order to be classified as renewable.

According to a delegated act from the European Commission (not decided at the time of writing, April 2022), it appears that there must be a temporal and geographical connection between electricity production and fuel production and that there should be an element of additionality. This means, among other things, that electricity-based hydrogen must be produced from new, additional renewable electricity in order to be classified as renewable.

Although this may seem unnecessary, as mentioned above, it is likely that the new electricity production required to cope with the electrification, including hydrogen production, will be based on additional wind power.

Appendix 8. Excerpts from the proposed Swedish national hydrogen strategy

The following list are excerpts of sections with high relevance for hydrogen pipelines in Sweden from the proposed Swedish national hydrogen strategy (Swedish Energy Agency, 2021b).

- The **cost gap between fossil and fossil-free** is a global challenge and one of the most important to manage in order for hydrogen to contribute to fossil-free industry.
- All in all, this market failure means that it is not always enough to put a price on emissions and support research and development, but that instruments may also be needed in the commercialization phase of new technologies so that the potential for cost reductions can be realised and the new technology can then carry itself.
    - Action: Investigation of the need for **additional policy instruments that reduce the cost gap between fossil-free and fossil hydrogen**
- As a complement to technical research and development, system studies, scenarios and modelling, techno-economic studies and life cycle assessments are needed
- Increased research **cooperation** at Nordic and EU level
- In the absence of natural geological conditions for l**arge-scale storage**, storage of hydrogen in Sweden can be expected to take place in conventional hydrogen storage tanks in close proximity to the use, in gaseous form or in liquid form. The storage technology that involves lined rock cavern can offer more large-scale storage but only after testing and evaluating the technology. It may also be relevant to investigate opportunities for hydrogen storage outside the country's borders, primarily within the Nordic region
- That the necessary **regulation** is put in place is a prerequisite, partly for the use of hydrogen to contribute to climate neutrality in a sustainable way, and partly to create clear rules of the game and thereby conditions for further investments.
- **Regulatory framework** for the production, distribution and storage of hydrogen should be investigated and adapted and updated with security in focus
- **Permit processes** for hydrogen plants and electricity lines need to be streamlined and lead times shortened

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