Strategy for fossil free competitiveness

HYDROGEN

Fossil Free Sweden

A strategy by
Fossil Free Sweden

HYBRIT
FOSSIL FREE STEEL

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Foreword

Hydrogen is on everyone's lips. Is it the new miracle medicine for eliminating fossil fuels throughout the world?

Why now, in that case, and what is its actual potential? This hydrogen strategy, developed by Fossil Free Sweden together with parts of the business sector will provide you with the answers to these questions, but if we were to already throw some light on this, it is the dramatic fall in price of renewable electricity that forms the basis of this expected hydrogen boom. When renewable hydrogen is now even expected to be cheaper than natural gas before 2030, it will be clear to everyone that hydrogen will be a real gamechanger.

And this is necessary. It is already five past twelve for the planet. The countries of the world must now hone their climate work if the world is to live up to the Paris Accord. We have become accustomed to talking about wind, solar, biofuel and energy efficiency, but now a new player has entered the arena. Now that hydrogen can be produced with renewable energy (fossil hydrogen is already being used) it will be an important piece of the puzzle in developing a completely fossil-free society. The EU has also recognised this. They have drawn up their own hydrogen strategy and are announcing an investment of EUR 430 billion. Enormous amounts that speak for themselves: The EU prioritises hydrogen.

But there are also other reasons behind the investment. Cheap hydrogen will be a key to strengthening the competitiveness of the many sectors through increased fossil freedom in the global market. These double reasons mean that hydrogen will be implemented faster than we can imagine.

Fossil Free Sweden, together with industry and transport sectors, has developed 22 roadmaps for fossil-free competitiveness, that are now to be implemented. But the roadmap puzzle does not fit together. For example, there is not enough forest for all the biofuel demanded by the roadmaps. Therefore, Fossil Free Sweden will produce a number of strategies to solve the puzzle of the 22 roadmaps.

Please note that this hydrogen strategy is not Sweden's national strategy, because there is no such strategy yet. However, it is Fossil Free Sweden's hydrogen strategy that large parts of the hydrogen value chain stand behind, and we hope of course that it can contribute to Sweden's own hydrogen strategy. Even more important is that the Swedish Government and the Parliament now remove the obstacles that have been highlighted so that Sweden can take the lead in hydrogen development. We have the natural conditions to be at the forefront even if we started late.

It is important to remember that no alternative alone can take us out of fossil dependence. But there is no longer any doubt that hydrogen will be an important complement.

Svante Axelsson
National Coordinator, Fossil Free Sweden

Companies behind the strategy

In its work, Fossil Free Sweden has had a dialogue with a number of companies, which stand behind the strategy as a whole, but not necessarily all individual formulations and proposed measures.

Anders Fröberg, CEO, Borealis Sverige
Andreas Bodén, Director Sales & Marketing, PowerCell Sweden AB
Andreas Gyllenhammar, Director strategy, innovation and sustainability, Jämtkraft
Andreas Regnell, Senior Vice President of Strategic Development, Vattenfall
Björn Aronsson, Managing Director, Vätgas Sverige
Göran Nyström, Executive vice president, head of group marketing and technology, Ovako AB
Hans Holmström, CEO, Siemens Energy AB
Hans Kreisel, CEO, Nordion Energi
Joachim Nordin, CEO, Skellefteå Kraft
Johan Svenningsson, CEO and Country Chairman Uniper Sverige, Uniper Sverige
Lars Lind, Managing Director, Adesso BioProducts AB
Madeleine Gilborne, Business Development Manager CleanTechnologies, Alfa Laval
Magnus Heimburg, CEO, Preem
Maria Malmkvist, CEO, The Swedish Gas Association
Markus Petäjäniemi, Director market and technology, LKAB
Martin Pei, CTO, SSAB
Martin Thordén, CEO GKN Aerospace Sweden AB
Martina Wettin, Founder, Nilsson Energy
Mats W Lundberg, Head of sustainability, AB Sandvik Materials Technology
Mattias Wärn, CEO and founder, Svea Vind Offshore
Nicklas Lång, Senior Vice President Sustainability, Höganäs AB
Olof Källgren, Market director, Linde GAS Region Europe North
Per Langer, CEO, Fortum Sverige
Per Rosenqvist, CEO, Statkraft Hydrogen Sweden AB
Per-Arne Karlsson, Director Public Affairs, St1 Sverige AB
Peter Ekholm, CEO, Inlandsbanan AB
Peter Lundström, CEO, Permascand AB
Peter Rydebrink, CEO, Euromekanik AB
Pia Sandvik, CEO, RISE Research Institutes of Sweden AB
Staffan Lundgren, Director, Technology Exploration and Strategy, Volvo Group Truck Technology
Susanné Wallner, ElectriVillage, Mariestad
Tomas Kåberger, InnoEnergy and Chalmers
Tony Sandberg, Research Director, Scania CV AB
Torsten Granberg, CEO Plagazi AB

22 roadmaps for fossil free competitiveness

In the roadmaps for fossil free competitiveness 22 sectors describe how they can contribute to the Swedish climate target of climate neutrality by 2045. Together they also show in what key areas decisive action needs to be taken in order to succeed with the transition in a way that strengthens competitiveness. Because of that, Fossil Free Sweden has developed horisontal strategies together with the actors in the different value chains to pave the way and show the road ahead.

CONCRETE INDUSTRY	AVIATION INDUSTRY	CEMENT INDUSTRY	AGRICULTURAL SECTOR	MINING AND MINERALS INUSTRY	STEEL INDUSTRY
SKI RESORT SECTOR	DIGITALISATION CONSULTANCY INDUSTRY	FOOD RETAIL SECTOR	HEAVY ROAD HAULAGE	HEATING SECTOR	MARITIME SECTOR
AGGREGATES INDUSTRY	CONSTRUCTION AND CIVIL ENGINEERING SECTOR	ELECTRICITY SECTOR	FAST-MOVING CONSUMER GOODS INDUSTRY	RECYCLING SECTOR	FOREST SECTOR
AUTOMOTIVE INDUSTRY LIGHT VEHICLES	AUTOMOTIVE INDUSTRY HEAVY VEHICLES	PETROLEUM AND BIOFUEL INDUSTRY	GAS SECTOR		

Summary

Sweden aims to have zero net emissions of greenhouse gases by 2045. As a step in this, 22 industries within the framework of Fossil Free Sweden have developed roadmaps for fossil-free competitiveness that show how they can increase their competitiveness by 2045 by becoming fossil-free. Now the focus is on implementing the roadmaps. There are still missing pieces of the puzzle and to enable rapid implementation of the roadmaps, Fossil Free Sweden, together with companies in affected value chains, is developing horizontal strategies that solve a number of challenges common to all industries, paving the way for development.

Hydrogen strategy for climate and industrial initiatives

This strategy is about the role hydrogen can play in strengthening Swedish industry's competitiveness in the transition to a fossil-free society and what policies are needed to promote hydrogen development.

The strategy highlights hydrogen as an important tool for achieving the climate goals but also as a focus for new industrial initiatives to create innovations, jobs and export products. Therefore, the focus is on refining industry products within the country's borders, rather than producing and exporting hydrogen to other countries. Investments in hydrogen are now taking place on a broad front, not least in the EU. The EU hydrogen strategy from 2020 presents very ambitious hydrogen development. The goal is to increase the installed electrolysis power for the production of renewable hydrogen in the EU from an estimated 1 GW in 2019 to 6 GW in 2024 and 40 GW in 2030 respectively, and another 40 GW by 2030 in the EU neighbourhood to meet EU needs.

Hydrogen today and in the future

The climate footprint of hydrogen is determined by the origin of the energy in combination with production technology. Fossil hydrogen (grey hydrogen) is produced from fossil fuels and renewable hydrogen ("clean" or green hydrogen) is produced by electrolysis from renewable electricity that splits water or from biomass or biogas.

The total use of hydrogen globally amounts to around 120 million tonnes annually and is mainly of fossil origin. It is primarily used as a raw material in the chemical industry for the manufacture of ammonia, methanol and other chemicals, as well as for various refinery and metallurgical processes. Less than 5 per cent is produced by electrolysis.

Hydrogen produced from fossil fuels but where carbon dioxide is captured using carbon capture and storage (CCS) technology is often referred to as "low carbon" or blue hydrogen. "Low carbon" may also refer to hydrogen from nuclear-generated electricity or a low-carbon electricity mix.

This strategy is about renewable hydrogen and the fossil-free part of "low-carbon" hydrogen, i.e. hydrogen from a Swedish electricity mix. The share of renewable hydrogen is expected to increase over time as Sweden's energy mix is converted to a higher proportion of wind and solar power and when the share of biogas in the natural gas grid increases further.

The cost of renewable electricity production is declining worldwide and is expected to continue to fall. The electricity price has a significant impact on the total cost of electrolysis-based hydrogen, but also the cost of the electrolyser itself and its utilisation degree are important. The electrolysis technology is constantly improving at the same time as the market for fossil-free hydrogen is growing. Now as the production rate increases and economies of scale are achieved, the cost of electrolysers is expected to be halved by 2030. In the places in the world where fossil-free electricity is cheap, fossil-free hydrogen is expected to be competitive with blue hydrogen within a few years or no later than 2030. According to one of Bloomberg's forecasts, Scandinavia has the potential to be one of these places. The proposal in the strategy is therefore that only fossil-free hydrogen should be rewarded. This does not imply a ban on blue or grey hydrogen, for example, but that regulations and support systems primarily reward investments in fossil-free hydrogen.

Expansion of the hydrogen infrastructure in the country can be accelerated by establishing cross-sectoral local and regional hydrogen clusters. They can be established where existing industries use or will use hydrogen and where infrastructure such as ports and railways already exist. It would thus be an establishment of what the EU strategy calls a Hydrogen Valley. Sweden establishing a nationwide hydrogen pipeline network and eventually becoming part of a "European Hydrogen Backbone" is not considered a realistic scenario, as Sweden, unlike many European countries, lacks natural gas networks that can be converted to pure hydrogen networks. Instead, it is planned over time to convert the Swedish natural gas grid on the west coast into a pure biogas network.

Major upcoming industrial initiatives

There are currently a number of major industrial projects in Sweden, where the production and use of hydrogen is, or is planned, to be central to one or more new value chains. Several new initiatives and partnerships have been announced in 2020 and more are expected in 2021. Here are some examples:

- HYBRIT's investment in fossil-free steel with hydrogen as a reduction agent, and LKAB's major industrialisation of the same technology for carbon-free sponge-iron.
- Ovako is preparing the next demonstration step for steel heating using fossil-free hydrogen.
- Both Scania and Volvo AB invest in the development of hydrogen-powered trucks.
- Perstorp's "Project Air", where together with Fortum and Uniper, they are developing a unique process for sustainable methanol production by combining CCU (Carbon Capture and Utilisation) and gasification.
- Preem and St1 are planning increased biofuel production using fossil-free hydrogen.
- St1, Liquid Wind and Jämtkraft are preparing for various investments in electrofuels.
- Nouryon plans to replace fossil hydrogen with fossil-free hydrogen for its hydrogen peroxide production.

This hydrogen strategy shows that today's known hydrogen projects in Sweden can achieve an emission reduction of just over 30 percent of Sweden´s national carbon dioxide emissions.

In addition to this, LKAB's future exports of sponge iron will be able to provide a reduction abroad that corresponds to almost 60 percent of Sweden´s total emissions. However, large amounts of renewable electricity will be required to produce all the hydrogen needed. It is a matter of 55 TWh of electricity in the known projects that have chosen electrolysis as the mode of production.

Cooperation between central government and the business sector

Sweden is well-placed to cope with this challenge, but then central government and the business sector need to work together. The strategy's action plan presents five areas with obstacles and proposals for policies to help industry to implement and keep up the pace of its hydrogen projects.

The electricity system is key to implementing hydrogen investments in several parts of Sweden. Electricity grid capacity is a limiting factor in several places, and in the long run, increased production of renewable electricity will be needed to meet the major industrial fossil-free hydrogen initiatives. Svenska kraftnät (the Swedish transmission system operator) should be tasked with developing an electricity grid plan that sets out which electricity lines are prioritised to cope with this.

A hydrogen infrastructure also needs to be developed, and since hydrogen pipelines are a relatively new type of infrastructure, new regulations are also needed. The Government should therefore instruct the Energy Markets Inspectorate to create regulation with a revenue framework for hydrogen pipelines. The expansion of hydrogen pipelines should be subject to concessions in the same way as electricity lines. The Government should also set up a planning goal to have 3 GW electrolysis power in place in 2030. The planning goal is not a nationally binding goal but an objective for government agencies to relate to.

In order to provide stable rules for hydrogen development, development of regulation and market conditions is also required. Taxation of production and distribution, as well as use, needs to be reviewed and the role of hydrogen in the green gas principle needs to be clarified.

A lot of investments are needed in hydrogen initiatives, and to start with they can result in higher costs than conventional investments. Therefore, the Government needs to contribute financing solutions and introduce various financial instruments so as to reduce the investment risk for companies. Consequently, the Government should carry out a fast-track study of the Carbon Contract for Difference, a system in which central government provides support based on the project's carbon reduction related to EU-ETS prices.

In addition, research and development will continue to be important as hydrogen is introduced into the market. There is also a need for skills enhancement within government agencies and other actors in society in relation to the new technologies and systems required for this development. For example, a coordinating agency for licensing issues related to hydrogen needs to be set up.

The implementation of the industry's initiatives and proposed policies represents an important contribution to Sweden's goal of climate neutrality in 2045 while strengthening Swedish industry, and can thus contribute to increased welfare.

Listed below are prioritised proposals for improving conditions for hydrogen development in Sweden (described in more detail in Chapter 9, which also include more proposals than the prioritised below):

1. **The right conditions for the electricity system is a key issue for fossil-free hydrogen production**
    - The Government should during 2021 instruct Svenska kraftnät (Swedish TSO) to develop an electricity grid plan that sets out which electricity lines are prioritised to enable industry to be electrified at a sufficiently high rate, and the timetable for laying the electricity lines.
    - The Government should during 2021 appoint a committee that is tasked with handling regulatory barriers that hamper attempts at new solutions based on new technologies or existing technologies used in new ways in 2021, a decision should be made that at least three electrical lines can be included in trials. This is in line with the proposals of the Committee for Technological Innovation and Ethics (Komet).
2. **New infrastructure required for hydrogen development throughout the country**
    - The Government should by 2022 set a planning goal to have 3 GW installed electrolysis power by 2030 and at least 8 GW by 2045 to enable fossil-free development in most sectors.
    - The Government should during 2021 instruct the Energy Markets Inspectorate to create regulation with a revenue framework for hydrogen pipelines. The expansion of hydrogen pipelines should be subject to concessions issued by the Energy Markets Inspectorate in the same way as electricity lines.
    - Review the law governing environmental permits so that the industries and energy establishments that already produce and use hydrogen on a large scale and who want to convert to a more climate-adapted production of hydrogen in the same closed industrial area only need to submit a change notification instead of currently having to apply for a new environmental permit.
3. **Development of regulations and market conditions can increase the pace of fossil-free hydrogen**
    - Starting in 2021, the Government should review the taxation of hydrogen, electrofuels

and electrochemicals, including production, distribution and various applications.

- The Civil Contingencies Agency (MSB) should during 2021 draw up national advice and recommendations for handling hydrogen and hydrogen pipelines to be used by all rescue services and municipalities.

4. **Several fossil-free hydrogen initiatives in need of financing solutions**

   - The Government should during 2021 carry out a fast-track study concerning production support for fossil-free hydrogen projects during an introductory phase through the Carbon Contract for Difference, a system in which central government provides support based on the project's carbon reduction related to EU-ETS prices.
   - The Government should during 2021 instruct the Swedish Energy Agency to draw up a call for proposals for regions in Sweden as demo-show rooms to test and demonstrate cross-sectoral hydrogen systems. The aim is to establish a couple of Swedish hydrogen clusters ("Hydrogen Valleys").

5. **Research, development and skills provision are key to long-term sustainability in several hydrogen value chains**

   - The Government should work towards increased coordination between agencies regarding permit issues linked to the hydrogen area, for example by appointing a coordinating agency.
   - The Government should ensure that universities and other higher education institutions continue to establish areas of research and innovation in the field of fossil-free hydrogen.

1. Introduction

Sweden aims to be one of the world's first fossil-free welfare countries and to have zero net emissions of greenhouse gases by 2045. As a step in this direction, 22 industries within the framework of Fossil Free Sweden have drawn up roadmaps for fossil-free competitiveness.

In the roadmaps, the industries show how they will become fossil-free by 2045 with increased competitiveness, and what measures they need to take themselves and what political conditions are needed to increase the pace. Now the focus is on implementing the road maps. But there are still missing pieces of the puzzle, such as the fact that forestry and agriculture are not sufficient for everything that is expected in the roadmaps. To enable rapid implementation of the roadmaps, Fossil Free Sweden is therefore developing horizontal strategies that solve a number of challenges common to all industries, paving the way for development.

Fossil-free hydrogen is the enabler of several industries' climate adaptation at the same time as it opens up new business and export opportunities. This hydrogen strategy identifies the issues and challenges that require national coordination so that different value chains and sectors can accelerate development, and which government decisions are needed to make Sweden one of the world's first fossil-free welfare countries.

Interest in fossil-free hydrogen is increasing in the world, and the development of hydrogen technologies and hydrogen-based system solutions for different sectors has accelerated in recent years. Fossil-free hydrogen is now considered to be a key component in the transition to a climate-neutral society within the EU but also in many other countries around the world. There are several different driving forces behind this rapidly growing interest. Fossil-free hydrogen has the potential to revolutionise by replacing fossil fuels and inputs, thereby reducing climate footprints, but also environmental footprints (for example sulphur dioxides, nitrogen dioxides and particles) from several industries, not least in the industrial sector. Hydrogen, produced via electrolysis, is also an enabler that can connect the various sectors of the future energy system and contribute flexibility in the form of energy storage, regulating and balancing power. Other underlying drivers are current technological development and the expansion of renewable power production (wind, solar) with falling electricity costs, while electrolysers are becoming increasingly efficient and cheaper. Since fossil-free hydrogen can be produced from both electricity and different types of biomass, the transition to hydrogen in the long run can also strengthen Sweden's security of supply.

Sweden is well positioned to become a prominent country in the development of hydrogen with the large proportion of renewable electricity production available and industrial know-how, as well as the targets of climate neutrality by 2045. If Sweden acts strategically in this development, new branches of industry can be created and existing ones can be developed, which will strengthen Sweden's competitiveness and welfare.

This is the reason why the government initiative Fossil Free Sweden has decided to develop a hydrogen strategy.

1.1. Implementation

This hydrogen strategy has been developed on the initiative and under the leadership of Fossil Free Sweden. The work has been carried out with support from the research institute RISE and the business community and is based on knowledge acquisition from literature, input from and discussions with the established reference group and other stakeholders from, for example, the chemical and refinery industry, the iron and steel industry, energy companies, the transport industry, technology suppliers, industry organisations and government agencies. Most of the company representatives also support the strategy, as listed in the introduction.

Members of the reference group: Mikael Nordlander, Vattenfall; Hans Kreisel, Nordion Energi; Jenny Larfeldt, Siemens Energy; Ulf Troedsson, Hydrogen Sweden and Tomas Kåberger, Chalmers/InnoEnergy.

1.2. Purpose and objective of the hydrogen strategy

The purpose and objective of this hydrogen strategy is to identify the obstacles and challenges that in the near future will require national policies, coordination or other measures, and to propose choices and measures to speed up the transition to a climate neutral and competitive Sweden. In this case, what has guided the choice of direction and priorities has therefore been the potential for reducing climate footprint in combination with creating growth and competitiveness.

FACTS ABOUT HYDROGEN

Hydrogen can be produced from reforming fossil fuels (natural gas, coal), biomass (solid biofuel, organic waste, biogas) and by electrolysis from electricity that splits water.

At water electrolysis, hydrogen, oxygen and heat are produced.

Today, there are mainly three different electrolysis technologies for the production of hydrogen from water: alkaline electrolysis (ALK), electrolysis with proton exchange membranes (PEM) and high temperature electrolysis (SOEC), of which the first two are available on an industrial scale in the commercial market.

Renewable hydrogen is produced from renewable energy or raw material. If also hydrogen originating from nuclear energy is included, the hydrogen is referred to "fossil-free hydrogen".

Hydrogen can be stored in compressed (ca 150-500 bars) or in liquefied form (-253°C) above ground or in underground hydrogen storages (rock cavities).

Hydrogen can be distributed via gas pipelines or road/train/sea transport. The hydrogen gas that is distributed in Sweden today occurs exclusively on road in compressed form.

2. Background

2.1. Hydrogen – basic information and definitions

Hydrogen is an energy carrier and input raw material that is part of many different existing and future value chains within:

- The processing industry
- The transport sector
- The energy sector
- The property and construction sector
- The agriculture and food sector

In the hydrogen strategy process, the focus is on value chains in the different sectors and synergies between them. Roughly what is included are production, storage and distribution of hydrogen for use in various sectors such as pure hydrogen, methanol or ammonia (Figure 1).

Hydrogen can be produced from fossil fuels, biomass or electrolysis from electricity that splits water. The origin of energy combined with production technology determines the climate and environmental footprint that is ultimately obtained. The EU hydrogen strategy[1] differentiates between renewable or "clean" hydrogen, fossil hydrogen and so-called "low-carbon" hydrogen. In everyday debate and in the open literature, there are also other names such as green, grey, blue and pink hydrogen, among others. The different definitions and names and how they relate to each other are explained in the following bullet list:

- **Renewable hydrogen or "clean" hydrogen:** Hydrogen produced from renewable energy or raw material. The renewable hydrogen can be produced from water and renewable electricity by electrolysis. It can also be produced by thermochemical reforming of biogas (instead of natural gas), or thermochemical or biochemical conversion of biomass, also known as bio-hydrogen. In the open literature, renewable hydrogen is also commonly referred to as green hydrogen.
- **Fossil hydrogen:** Hydrogen produced from fossil fuels, usually by natural gas reforming or carbon gasification. In the open literature, fossil hydrogen gas is also often referred to as grey hydrogen.

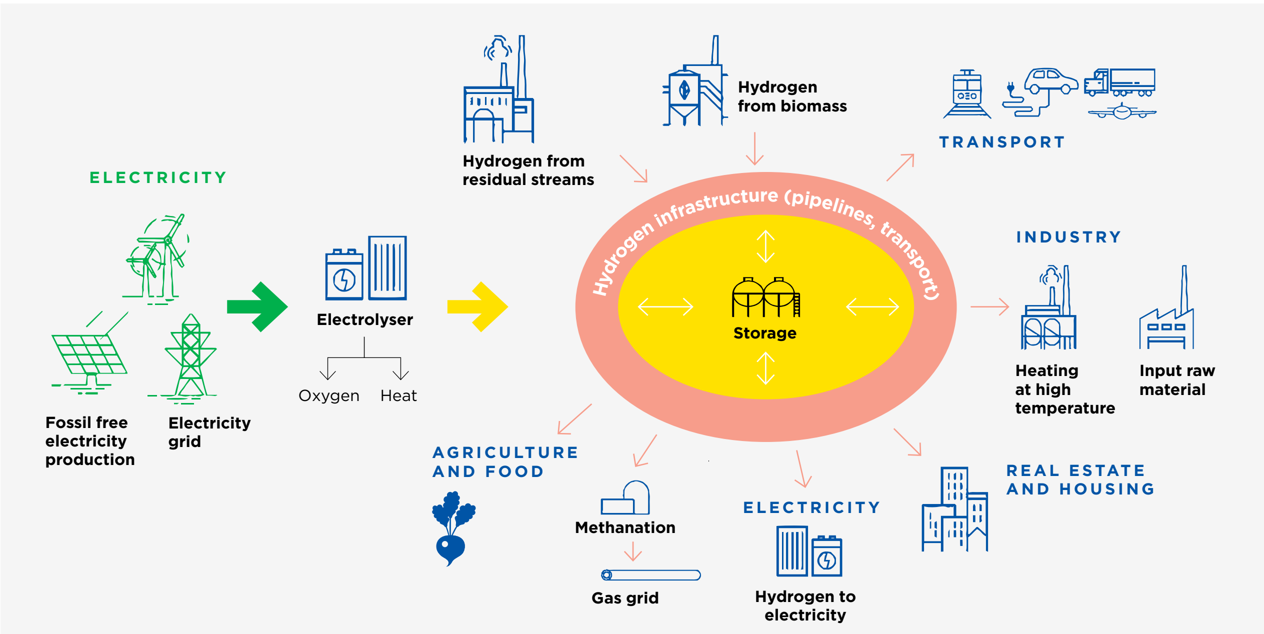


Figure 1: Hydrogen value chains, which are taken into account in this hydrogen strategy.

- **"Low-carbon" hydrogen:** This includes hydrogen with two different origins. Blue hydrogen, which is produced from fossil sources in combination with the capture of carbon dioxide, known as CCS technology (Carbon Capture and Storage). In November 2020, the European Commission announced that hydrogen produced by electrolysis from water and electricity, where electricity is derived from nuclear power or an electricity mix of low carbon content, is called "low-carbon" hydrogen. In the open literature, hydrogen derived from nuclear power, or an electricity mix with both renewable and nuclear power, is often referred to as pink or fossil-free hydrogen.

The renewable and the fossil-free part of the "Low-carbon" hydrogen is in focus in this strategy. The proportion of renewable hydrogen is expected to increase over time as Sweden's energy mix is converted to a higher proportion of wind and solar power and the share of biogas in the natural gas grid increases further.

Against this background, if renewable electricity/hydrogen has not been explicitly stated, the term fossil-free electricity/hydrogen is used throughout the document, which means hydrogen produced from the Swedish electricity mix or from biomass.

FACTS HYDROGEN – MAGNITUDES AND UNIT CONVERSIONS

1 ton hydrogen = 1111 Nm3 hydrogen = 33 MWh hydrogen

1 TWh hydrogen = 1000 GWh hydrogen= 333 333 333 Nm3 hydrogen = 30 000 tons hydrogen

An electrolyser with an efficiency of 65 percent needs 1,54 TWh of electricity to produce 1 TWh of hydrogen.

To produce 1 TWh hydrogen in one year, an electrolyser of 180 MW of electric input power is required, assuming the operating time of 8400 hours. The electrolyser then has an output of 120 MW hydrogen, i.e. 0,65 MW hydrogen/MW electricity, in accordance with the efficiency of 65 percent.

2.2. Hydrogen production and use – current situation

Hydrogen is already being produced and used today. The total use of hydrogen globally amounts to approximately 120 million tonnes annually, of which approximately 70 million tonnes (corresponding to about 2300 TWh of hydrogen) are derived from specific hydrogen production and the remainder from various industrial residual streams. The hydrogen, which is mainly of fossil origin, is primarily used as a raw material in the chemical industry for the manufacture of ammonia, methanol and other chemicals, as well as for various refinery and metallurgical processes. Less than 5 percent is produced today by electrolysis.[2] Replacing all the hydrogen used with fossil-free hydrogen from electrolysis would require about 4000 TWh of fossil-free electricity production and result in an emission reduction of approximately 800 million tonnes of carbon dioxide per year, equivalent to 2 percent of global emissions.[3]

In the EU27, hydrogen use amounts to approximately 10 million tonnes (equivalent to 339 TWh) per year and

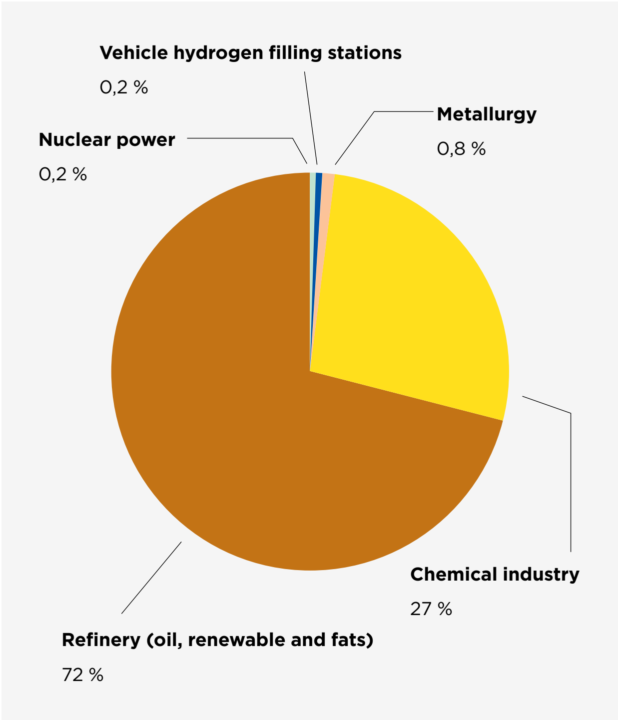


Figure 2: Overview of hydrogen use and production in Sweden today.

today constitutes about 2 percent of the total energy supply.[3,4] Specific hydrogen production constitutes 200 TWh, and producing it via electrolysis instead requires just over 300 TWh of fossil-free electricity production, and would provide an emission reduction of 1-2 percent of EU carbon dioxide emissions.[5]

Like the rest of the world, the chemical and refinery industry is responsible for most of the hydrogen produced and used in Sweden (Figure 2). It is also clear that today's direct use of hydrogen as vehicle fuel or in metallurgical industries constitutes only a very small proportion, approximately 1 percent combined.

As illustrated in Figure 3, production and use in Sweden amounts to around 180,000 tonnes of hydrogen per year (equivalent to about 6 TWh/year hydrogen) and is mainly of fossil origin (almost 67 percent through thermochemical conversion of natural gas). The second largest source of hydrogen in Sweden is industrial residual streams, while just under 3 percent is produced via electrolysis today.

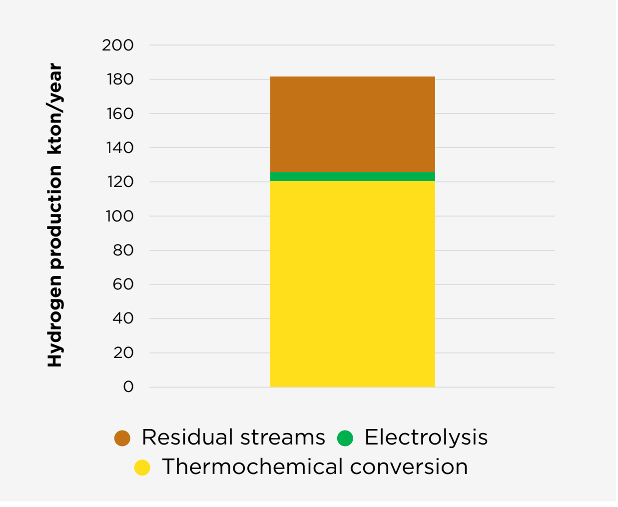


Figure 3: Summary of total hydrogen volume produced and used in Sweden today and the distribution between different production technologies.

Almost all hydrogen produced in Sweden is used near the location where it is produced. The map (Figure 4) shows where hydrogen is produced and used, as well as the production technology.

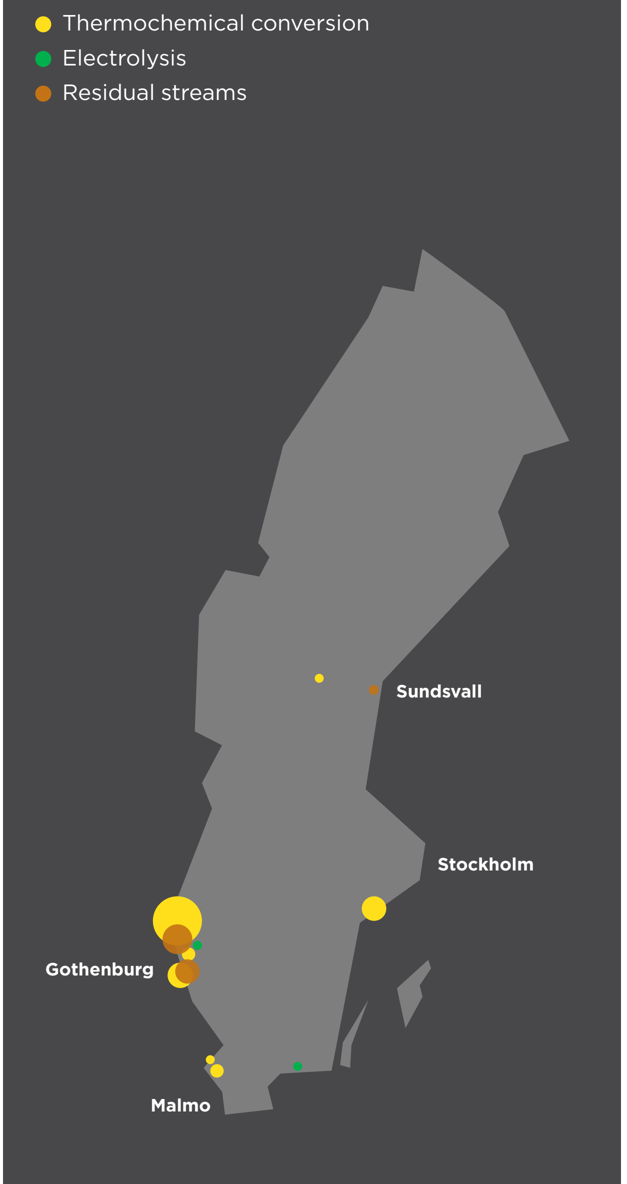


Figure 4 : Schematic image of where hydrogen is used and how it is produced in Sweden today. Users with hydrogen volumes under 200 tonnes/year have not been included on the map, however they are included in aggregated data at the national level. Examples of what is not visible on the map are nuclear power plants, hydrogen storage stations in five locations in Sweden (Arlanda, Gothenburg, Mariestad, Sandviken and Umeå) and parts of Linde's production.

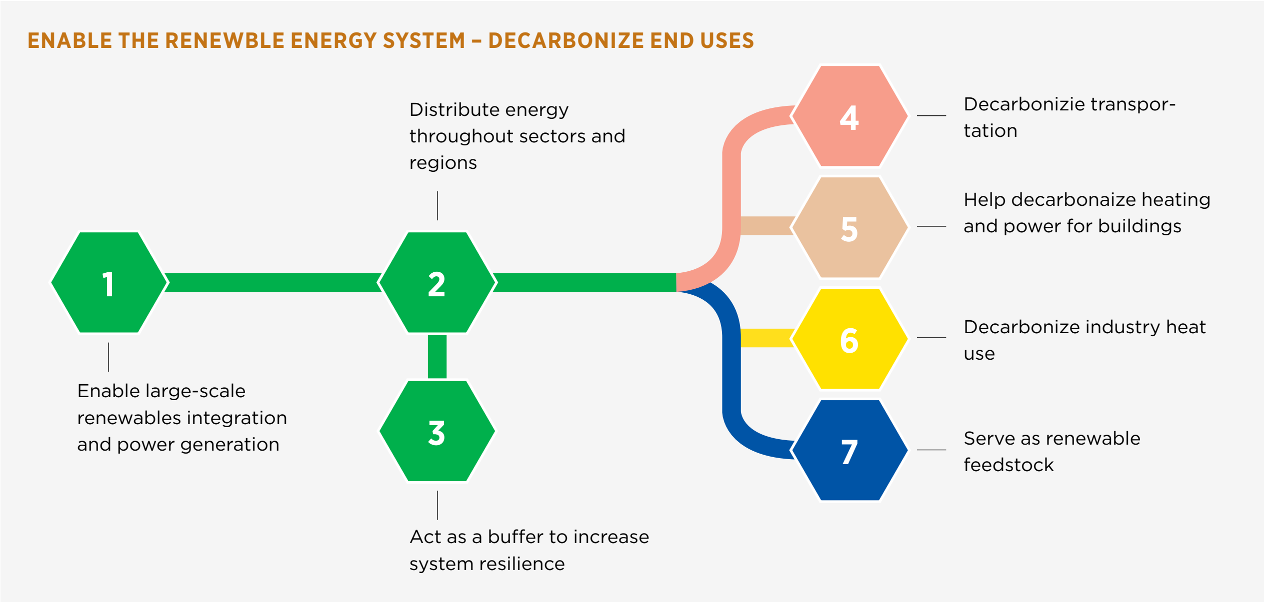


Figure 5: The role of hydrogen in the fossil-free energy system as described by Hydrogen Europe. Source: Hydrogen Europe.

2.3. International perspective

2.3.1. EU hydrogen strategy

The EU hydrogen strategy was announced in July 2020[1]. The strategy is an action plan for how the EU can combine forces to make renewable hydrogen technology a competitive solution to phase out fossil sources in different sectors, focusing on the industrial and transport markets (Figure 5). It complements the Commission's energy system integration strategy[6], and forms part of the plan for how the ambitions and objectives described in the European Green Deal[7], New Industrial Strategy for Europe[8] and its recovery plan[9] can be realised.

The European Strategy presents highly ambitious hydrogen development with the aim of having an installed electrolysis power for the production of renewable hydrogen within the EU corresponding to 6 GWel in 2024 and an additional 40 GWel in the EU neighbourhood to meet EU needs in 2030. This expansion in turn requires both a massive expansion of renewable electricity production and enhanced electricity grids. The total installed electrolysis power was estimated by the EU Joint Research Centre (JRC) to be about 1 GWel in 2019, with average annual growth of about 20 percent between 2016-2019[4]. According to FCH JU (Fuel Cells and Hydrogen Joint Undertaking) hydrogen could account for up to 24 percent of the EU's total energy supply in 2050[5]. Given that all hydrogen is produced via electrolysis, the EU estimates that up to one quarter of renewable electricity production in 2050 will be converted to hydrogen[1]. The estimate of electricity production in 2050 varies but in the future scenario where it grows most, where electrofuels (see Chapter 3.1) expand, it becomes 2.5 times larger than today (i.e. 7000 TWh)[10]. This would in turn entail a need of up to 1700 TWh of renewable electricity production for hydrogen production via electrolysis by 2050. This represents a 120 percent increase compared to current renewable electricity production in the EU27 (800 TWh in 2018)[11].

The European strategy advocates giving priority to the production and use of renewable hydrogen, mainly from wind and solar power. The strategy states that "low-carbon" hydrogen may be needed during a transition phase in order to quickly reduce emissions from existing fossil hydrogen production and to support the simultaneous development of renewable hydrogen technology.

The strategy proposes that hydrogen development and infrastructure development primarily take place via industrial clusters (usually referred to as hydrogen valleys) which, as of the mid-2020s, are connected via pipeline networks with supplementary road and sea transport. The vision is in line with what gas grid owners from nine European countries, including the Swedish Nordion Energi, present in the report ”European Hydrogen Backbone”.[12] It is based on the fact that existing natural gas infrastructure on the continent can be modified to transport hydrogen at an affordable cost. The target for 2040 is a European hydrogen network of 23,000 kilometres, of which 75 percent constitutes modified natural gas pipelines, which are connected to new hydrogen pipelines (25 percent). In the end, in a climate-neutral EU, according to this vision there would be two parallel gas transport networks; one dedicated for hydrogen and one for (bio) methane (methane produced from renewable raw materials either by anaerobic digestion or gasification with subsequent upgrading, holding similar quality as natural gas). The injection of hydrogen in existing natural gas grids is expected to occur only to a very small extent in decentralised production and in local gas networks during a transition phase, as end-users have difficulty in using a mixture with existing process infrastructure.

The European transition through hydrogen is expected to require investments of between EUR 180 and 470 billion up to 2050, of which EUR 3-18 billion for the production of low carbon hydrogen produced from fossil sources using CCS (blue hydrogen). In order to adapt the hydrogen production of various future end-users, such as in the steel industry or the roll-out of hundreds of new hydrogen filling stations, additional investments up to one billion euros are expected. To facilitate the realisation of the strategy, the Commission has also launched the European Clean Hydrogen Allliance,[13] which aims to coordinate and create an implementation plan for investments in hydrogen production on a larger scale and support demand for renewable hydrogen. Several Swedish organisations have already joined the alliance. The EU predicts that the investment in hydrogen will create a market worth thousands of billions of euros by 2050, and contribute up to one million new jobs.

1 Define en EU wide terminology for renewable and low carbon hydrogen together with a methodology to calculate life cycle greenhouse gas emissions in order to enable a functioning clean hydrogen economy

2 Establish the principle of carbon dioxide as the new “currency” of the energy system

3 Promote and support hydrogen market stimulation programs including quotas/targets, dedicated programs and support schemes

4 Enable a competitive hydrogen economy by clarifying the market design and supporting sectoral integration

5 Revise the Trans-European Network for Energy (TEN-E) Regulation to support the development and roll out of hydrogen networks

6 Revice the deirective for the Deployment of Alternative Fuels Infrastructure (DAFI) to boost the use of hydrogen in the mobility sector

7 Support for a strong, effective and alla-encompassing Clean Hydrogen for Europe Partnership

8 Remove undue barries to hydrogen production and hydrogen infrastructure

9 Unlock hydrogen´s potential by leveraging innovative financial instruments

10 Launch the Clean Hydrogen Alliance and establish hydrogen as a key element in global EU climate diplomacy and neighbourhood policy

Figure 6: Summary of the EU Action Plan on Green Hydrogen. Source: Hydrogen Europe.

2.3.2. Forthcoming EU regulations

As part of the EU Green Deal, the European Commission is now reviewing a number of regulatory frameworks and directives that will have an impact on Swedish hydrogen development. This includes the EU's ongoing revision of state aid rules[14] that have an overall impact. Also of great importance is the ongoing revision of the Renewability Directive (REDII) and underlying Delegated Acts[15]. The revision of the Renewability Directive is expected to clarify how the production and use of renewable biofuels will be treated and how the demand for "low-carbon" hydrogen in relation to renewable hydrogen will develop. It is also expected to show how the production of electrofuels and electrochemicals will be handled in relation to emission calculations. Therefore, the revision of the Renewability Directive has a major impact on the development of related technologies and markets. At the same time, a review is now in progress of the Energy Tax Directive (ETD)[16] aimed at better adapting and promoting the development of renewable fuels, including renewable gas. Other examples are the revision of the Alternative Fuels Infrastructure Directive (AFID)[17] in combination with the Trans-European Transport Network (TEN-T) regulatory framwork,[18] which is expected to contribute to an accelerated development of, for example, hydrogen refuelling stations and charging stations by encouraging EU countries to develop action plans for the expansion of infrastructure for alternative renewable fuels that are in line with the Paris climate targets and the Green Deal. Finally, the design of the taxonomy is extremely important, not least as regards biofuels, and the future planned revisions to carbon dioxide requirements for heavy duty and light vehicles are crucial for the calculation of hydrogen emissions.[19] All the new versions of the above-mentioned regulations, except for the vehicle requirements, will be presented at different times in 2021.

2.3.3. Other national hydrogen strategies - examples

As mentioned initially, a number of countries have in recent years made decisions on national strategies and major investments in the field of hydrogen. The strategies show how the countries want to create conditions for the area based on nation-specific climate and environmental goals combined with other drivers to strengthen the countries' competitiveness. In some of the strategies, expected hydrogen needs are presented for the year 2030. Some countries also present targets for their own hydrogen production, but also for imports. Some examples are given below.

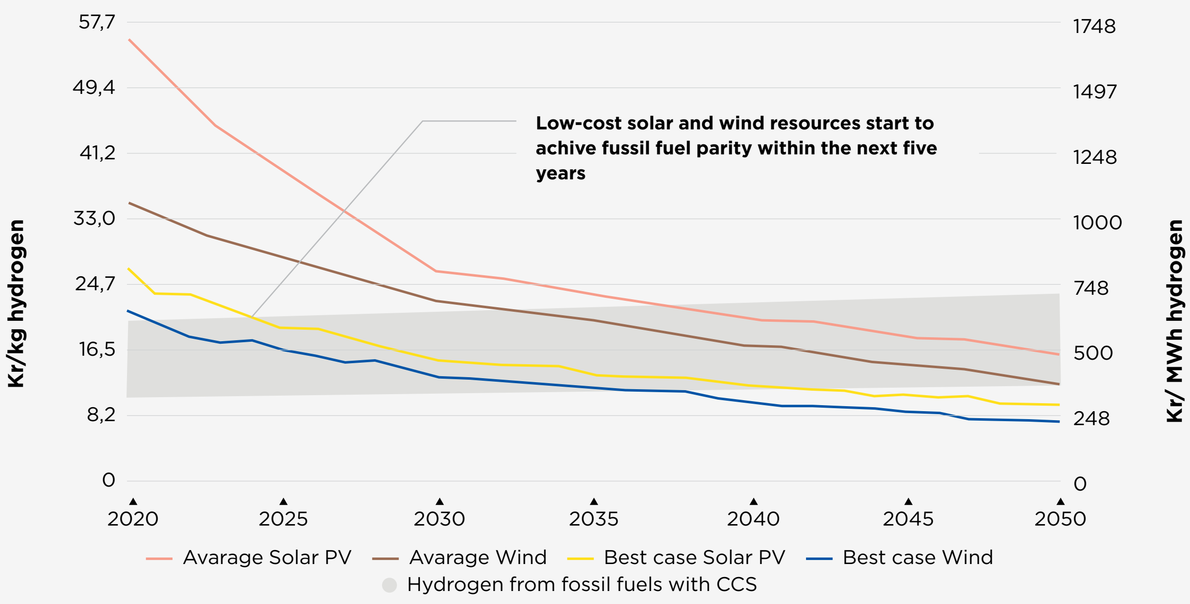
Norway sees great potential in both blue and renewable hydrogen, and in its hydrogen strategy, which was presented in the spring of 2020, has a stated goal of working to achieve the same market conditions for blue hydrogen as renewable hydrogen in the European arena. No estimates of future national hydrogen needs, export volumes or targets for production are given. In the maritime sector, large parts of the value chain are represented in Norway and the strategy highlights this as particularly interesting, where hydrogen or ammonia can replace batteries or liquefied natural gas.[20]

Finland presented a roadmap for hydrogen in October 2020 that is to form a basis for a national climate and energy strategy that is expected to be presented in summer 2021. The roadmap provides a 10-year outlook for national production and use of low-carbon hydrogen, and highlights comparative advantages such as good wind power assets, strong transmission networks for electricity, a stable and predictable regulatory framework, and long experience in industrial hydrogen use. The roadmap proposes that fossil hydrogen be gradually phased out through taxation and policy instruments, combined with the hybridisation of existing fossil-based hydrogen production with electrolysers and local hydrogen storage. The potential for renewable hydrogen production in Finland is estimated at 100,000-150,000 tonnes (approximately 3-5 TWh hydrogen) in 2030 without taking into account any new use in industry or transportation.[21]

In Denmark's strategy, the strong domestic wind power industry and the transition of aviation and other heavy transport sectors are in focus with the ambition to reduce the country's carbon dioxide emissions by 2.5 million tonnes.[22] For example, Ørsted, Mærsk and SAS are planning large-scale production facilities of 1.3 GW outside Copenhagen. In addition, the Danish government plans to build energy islands in the Baltic Sea and the North Sea corresponding to a total wind power output of 5 GW, which will be used for hydrogen production.[23]

The Netherlands' hydrogen strategy, presented in March 2020, stresses the country's comparative advantage as a trading nation with resources for producing, distributing and storing hydrogen, where the port of Rotterdam is considered particularly important as an international energy trading hub. The Netherlands is strongly fossil-dependent and the government emphasises the importance of both prioritising the development of infrastructure and large-scale production of blue hydrogen by 2030 and paving the way for the development of renewable hydrogen, both within and outside the country. In September 2020, the Netherlands signed a cooperation agreement with Portugal for the development of a strategic import-export value chain for renewable hydrogen, where the first step for the two countries is to develop a joint application within the IPCEI scheme (EU's Important Project of Common European Interest (the EU initiative "Important Projects of Common European Interest," for more information on IPCEI, see Chapter 6).[24]

As the last example, Germany's ambitious hydrogen strategy can be mentioned, with a clear focus on transitioning through renewable hydrogen and a goal of establishing the country as a global leading supplier of hydrogen technologies. The German government estimates a need for approximately 90–110 TWh of renewable hydrogen by 2030. To cover some of this need, Germany plans to install 5 GW electrolysis, supplied with electricity from onshore and offshore wind power equivalent to 20 TWh. The remaining and largest share of the hydrogen requirement (about 85 percent) is planned to be imported from production in other countries. They have investment plans in place for the establishment and commissioning of dedicated hydrogen networks in north-western Germany already in 2023, and a clear plan for the expansion of filling stations, where they will have installed 100 hydrogen refuelling stations by the end of 2020.[25]



Notice: Remaining CO2 emissions are from fossil fuel hydrogen production with CCS 6345 kr/kWel (2020); 4450 kr/kWel (2030); 3584 kr/kWel; 3049 kr/kWel (2050).

Electrolyser costs: 412 kr/kW input power (2030); 824 kr/kW input power (2040); 1648 kr/kW input power (2050).

Prices are converted from USD to SEK (kr) based on the exchange rate 8,24 kr/USD (2021-01-10)

Figure 7: The future production cost for renewable hydrogen, given different assumptions about price development for wind and solar power, respectively. The figure also shows a range specified for the production cost of blue hydrogen. Since a certain share (about 10 percent) of the carbon dioxide is not captured at the blue hydrogen production plant, there is a carbon dioxide cost. Source: IRENA 2019.[26]

In their hydrogen strategies all countries, as well as the EU, emphasise the importance of increased international cooperation and coordination, the need for new infrastructure, harmonisation with regard to regulations and standards (see examples in Chapter 2.3.3. and 8), as well as continued investments in research, development and demonstration for production, storage, distribution and end-use in different sectors.

2.4. Cost trend for fossil-free hydrogen and its impact in the customer chain

2.4.1. Cost trend for fossil-free hydrogen

Fossil-free hydrogen from electrolysis is today more expensive (approximately 2-4 times on average according to the EU hydrogen strategy from 2020[1]) than fossil-based hydrogen, and is strongly dependent on the price of electricity, the electrolyser's investment cost and utilisation degree. The share of the production cost that is currently controlled by the electricity price depends on the exact operating conditions, but the trend is currently towards 70-75 percent, assuming a high utilisation degree.

As electrolysis technology improves, the market for fossil-free hydrogen grows, the rate of production increases and economies of scale are achieved, the cost of electrolysers is expected to be halved by 2030[1]. In the places in the world where fossil-free electricity is cheap, hydrogen from wind power is expected to be competitive with blue hydrogen as early as in 2022 and hydrogen from solar power in 2024 (Figure 7). According to one of Bloomberg's forecasts, Scandinavia has the potential to be one of these places (Figure 8).

Blue hydrogen will always be more expensive than fossil hydrogen as the cost of CCS is added and unlike hydrogen from electrolysis, no major price development is expected to take place over time for the blue hydrogen technology (Figure 7). On the contrary, the costs of blue hydrogen are even expected to increase a couple of percent. A primary explanation for this difference in development lies in the fact that blue hydrogen technology from the start is based on large-scale plants and, unlike fossil-free from electrolysis, both the learning curve and the scalability, which over time press down the price, are marginal.

As mentioned above, the utilisation degree (the number of operating hours per year) of installed electrolyser capacity has a great impact on what the hydrogen ultimately costs. The higher the utilisation degree, the lower the cost per MWh produced hydrogen because the specific investment cost then accounts for a greater

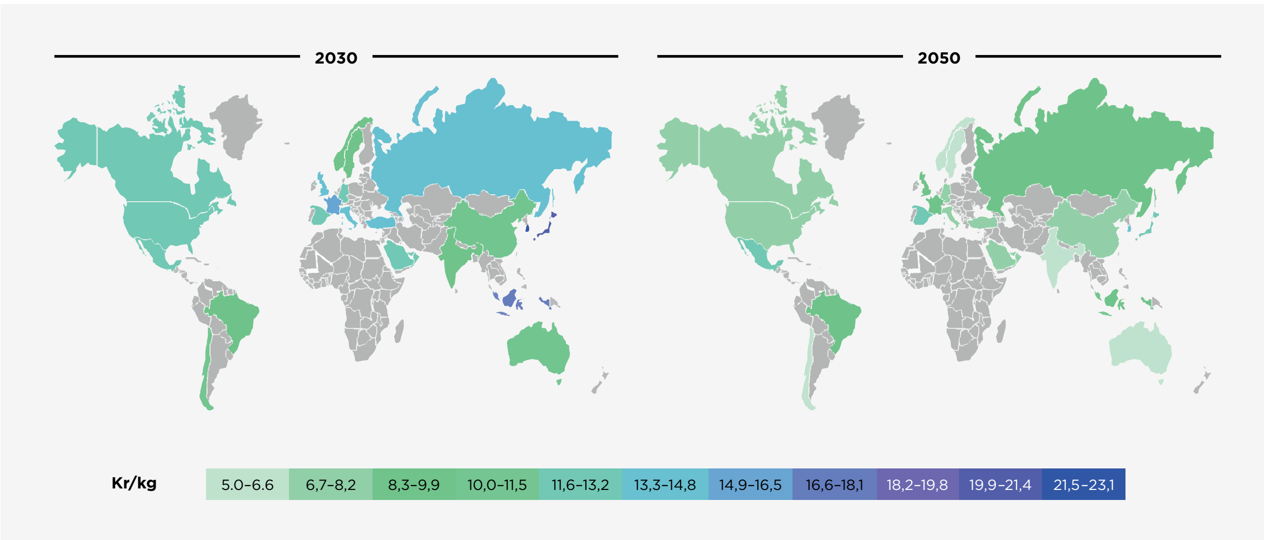


Figure 8: Forecast for production cost of hydrogen from electrolysis for different parts of the world for 2030 and 2050 respectively, given different, according to BloombergNEF itself optimistic, electricity price scenarios. Source: BloombergNEF.[27]

production quantity. This in turn means that the more the investment cost for the electrolyser drops, the more economic it will be to adapt hydrogen production to electricity supply and price.

Electrolysers can have different characteristics. Electrolysers with low capital cost per watt, low efficiency, and low capacity factor can compete only by producing at low electricity prices, while others with high capital cost per watt but high efficiency are used most of the year.

In the long term, large-scale thermochemical conversion of biomass (for example branches and tops, or other organic waste) can be a complement to renewable hydrogen production (called bio-hydrogen). The production cost in this case is linearly dependent on the price of the input biomass. Based on for example Gobigas and E.ON's B2G project, the cost picture is around SEK 600/MWh of hydrogen (corresponding to SEK 20/kg hydrogen) from GROT, which costs around SEK 180/MWh. More than half of this cost derives from investment and operating costs.[28] One advantage of this process is that it also opens up to create negative emissions by applying bio-CCS to the biogenic carbon stream that arises (described in more detail under 3.7.2), which in turn may reduce the costs of renewable hydrogen production. In cases where bio-CCS is implemented in the production of bio-hydrogen, the product gas is deemed to be "climate-positive" hydrogen.

2.4.2. Fossil-free hydrogen impact on the cost of processed products in the customer chain

Hydrogen as input raw material in industrial processes has the potential to be used (described in chapter 3.1) largely in processes for the production of basic materials such as metals and plastics. These basic materials are typically bulk goods and often have a relatively low value and are often traded on highly competitive international markets, making them sensitive to cost increases. In the case of fossil-free steel, HYBRIT states that raw steel produced with the HYBRIT process is expected to have a production cost 20–30 percent higher than the conventional blast furnace process, given the boundary conditions (electricity price, emission allowance price, coke coal price) that prevailed at the time of the study.[29]

However, an important aspect is that the subsequent steps in the value chains of base materials involve processing and result in products with higher value than the cost increase for input fossil-free base materials. In the example of fossil-free steel, a cost increase in the steel of 20-30 percent in practice amounts to about SEK 1,000-2,000 per tonne. For a car that contains about one tonne of steel and at the end-customer stage has a value of SEK 300,000-400,000 it means a cost increase to the consumer of far below 1 percent. Even though fossil-free materials are more expensive than materials with a large carbon footprint, there may be great opportunities to absorb this cost and compensate it through a marginal price increase at the end-customer stage – but at the same time with a significantly reduced carbon footprint for consumption.

The same logic applies, for example, to plastic materials, where value added can increase very much, but where value chains can at the same time be complicated, with many steps from basic chemicals to final product. For example, the Energy Transitions Commission[30] has calculated that even if the cost of ethylene, which is the most common base chemical in plastic, increases by 50 percent, the cost increase in a beverage bottle is only around 0.1 SEK.

The Energy Transitions Commission has also calculated that the additional cost it entails to totally eliminate global emissions from heavy industry (steel, cement, petrochemistry, aluminium) and heavy transport (aviation, shipping, heavy land transport) is less than 0.5 percent of global GDP. In comparison, the Stern report[31] concluded that the cost of damage from a changed climate due to not dealing with emissions is 5–20 percent of global GDP.

3. New value chains with hydrogen in Sweden

In the roadmaps developed within the framework of Fossil Free Sweden the branches of industry have described how they are to increase their competitiveness by becoming fossil-free. Hydrogen technologies are one of the measures expected to contribute cost-effectively to reducing emissions in an industry or process, which gives reason now for several industries and companies to see good prospects for investments in hydrogen.

There are currently a number of major plans and ongoing industrial projects in Sweden, where the production and/or use of hydrogen is central to one or more new value chains simultaneously. Several new initiatives and partnerships were announced in 2020 and, like the rest of Europe, development is now increasingly moving towards the installation of large-scale industrial facilities (up to several MWel) without any previous pilot and demonstration phase.

A summary is given below with examples of what was upcoming at the end of 2020 in the different industries in Sweden, focusing on the purpose and milestones, size and potential climate gains of the different value chains. For the more concrete plans and projects, an aggregated picture is also presented in Chapter 3.6, on which several of the strategy's proposals for action are based.

FACTS ELECTROFUELS AND ELECTROCHEMICALS

Electrofuels or electrochemicals are collective names for various synthetic fuels or chemicals (methane, methanol, Fischer-Tropsch fuels, ammonia, etc) and are in the EU commonly referred to as fuels of non-biological origin.

Carbon-based electrofuels or electrochemicals such as electromethanol can be produced by reacting hydrogen with carbon dioxide separated from, for example, industrial flue gases, biogas or fermentation plants.

The product quality and composition for electrofuels or electrochemicals is the same or similar as for the corresponding fossil or biobased alternatives.

3.1. Examples in the process industry

3.1.1 Examples in the chemical and refinery industry

The Swedish fuel industry, through its roadmap, aims to become climate neutral by 2045 with the milestone of climate-neutral operations, in the form of depots, logistics and marketplaces, as early as 2030. In 2019, the refinery sector accounted for 4.6 percent of Sweden's greenhouse gas emissions, while the chemical industry accounted for 2.8 percent.

Renewable or low-carbon hydrogen is a requirement for transforming the chemical and refinery industry. The following describes examples of different value chains and projects that are now being investigated in Sweden.

Hydrogen as input raw material for production of biofuels:

When upgrading biomass, more hydrogen is generally required, in the order of 3-4 times, than when fossil raw material is used. Preem, for example, aims to produce 5 million m^3 biofuels by 2030, corresponding to a total hydrogen balance of about 5 TWh per year, and is now investigating various initiatives and measures to be able to meet this target at its refineries in Lysekil and Gothenburg. The investigations include optimising conventional hydrogen production from various fossil sources as well as biogas, with and without associated CCS, and hydrogen from electrolysis. St1 Sverige AB is also investing heavily in the production of biofuels and has recently expanded its hydrogen production for its new biorefinery in Gothenburg. Hydrogen is produced today from natural gas from the gas grid with the intention of being replaced with hydrogen from electrolysis over time. Investments in fossil-free hydrogen in the production of biofuels provide a lower climate footprint for the biofuel. These investments are ultimately repaid because the reduction obligation rewards climate benefit.

Hydrogen as an input raw material for production of electrofuels and electrochemicals:

In addition to biofuel production, the chemical and refinery industry is also showing interest in electrofuels/electrochemicals.

Electrofuels or electrochemicals are a collective term for various synthetic fuels or chemicals (methane, methanol, etc.) that can be produced by allowing hydrogen to react with carbon dioxide that is separated from industrial flue gases, biogas or fermentation plants, whose quality and composition are of the same or similar quality as corresponding fossil or biobased alternatives. Electrofuel/electrochemical production is a form of CCU (Carbon Capture Utilisation), and the concept is a high-priority development area within the EU and is deemed to be a valuable potential complement to biomass production.

One example is St1, which has initiated a new cooperation project in the area of electromethanol in Finland. An electrofuel concept, including electrolysis for hydrogen production, may be implemented at their biorefinery in Gothenburg at the earliest in 2025. There are also plans to establish large-scale electromethanol plants at Swedish pulp and paper mills and/or combined heat and power plants. The company Liquid Wind is now investigating the possibility and aims to establish 10 electromethanol plants in Scandinavia by 2030. Their first plant, with an annual production of 50,000 tonnes of methanol is planned to be operational as early as 2024 and will be located adjacent to Övik Energi's Hörnebergsverket.[32] Another example of potential electrofuel production in Sweden is the pilot study that the energy company Jämtkraft is now running for the production of aviation fuel next to one of their combined heat and power plants in Östersund. Producing electrofuel for aviation, shipping and other heavy traffic is something that, for example, Denmark is now investing heavily in with a gradual upscaling of electrolysis power from 10 MWel in 2023 to 1300 MWel on a full scale, where one aim of the initiative is to be able to produce 30 percent of Denmark's aviation fuel needs already in ten years[33].

Hydrogen as fuel and input raw material in the chemical industry:

Hydrogen from electrolysis, as well as hydrogen and other carbon sources (hydrocarbons, carbon dioxide) in residual gases, are important input raw materials, but also fuels, in the transition to sustainable chemistry. One example is Perstorp's "Project Air" initiative in which a unique process for sustainable methanol production has been developed by combining CCU and gasification. In this case, biogas, different types of industrial residual streams containing hydrocarbons and carbon dioxide and hydrogen from electrolysis are used as raw materials. In November 2020, it was announced that in cooperation with Fortum, Uniper and the Danish biogas supplier Nature Energy, they are planning to establish a large-scale plant based on the current process in Stenungssund, including an installed electrolyser power of 25 MWel. The goal of the project is to be able to replace all the fossil methanol that Perstorp currently uses as input raw material in Europe (200,000 tonnes per year) which would lead to a potential annual carbon reduction of about 500,000 tonnes calculated for the entire project. The plant is expected to be operational in 2025 provided that funding from the EU is granted.[34] Moreover, Nouryon is investigating the conditions for converting from fossil hydrogen to hydrogen from electrolysis in its hydrogen peroxide production plants in Bohus and Ånge, which would correspond to a potential carbon dioxide gain of 75,000 tonnes per year. A third example of a new potential hydrogen application in the chemical industry is Borealis' collaboration with Vattenfall to investigate the possibilities of using hydrogen from electrolysis as a cracker fuel (equivalent to 300-500 MWel) as a replacement for the fossil gas currently used.[35]

3.1.2. Examples in the iron and steel industry

The steel industry writes in its roadmap for fossil-free competitiveness that they will become climate neutral by 2045. In 2019, the industry accounted for 12 percent of Sweden's emissions and the iron and steel industry


HYDROGEN
H2 FUEL

globally accounts for 8 percent of the world's emissions[36] which means that fossil-free solutions now being developed have great potential for global emissions reductions. As early as 2018 when the roadmap was launched, hydrogen was seen as an essential part of the solution for SSAB, which would thereby reduce Sweden's emissions by approximately 10 percent. The steel industry sees an increased demand for fossil-free steel when several value chains must adapt, and despite a higher production cost for fossil-free steel, it only affects the end product, for example a passenger car, by less than one percent (see Chapter 2.4.2).

Fossil-free hydrogen will be central to the future iron and steel industry in Sweden, both as input raw material and fuel, which is exemplified below:

Direct reduction with hydrogen for production of sponge iron and pig iron:

The most well-known hydrogen investment in Sweden is HYBRIT (Hydrogen Breakthrough Ironmaking Technology) which is a joint venture company jointly owned by SSAB, LKAB and Vattenfall. HYBRIT aims to develop a fossil-free steel value chain. In the process, the blast furnace process, where fossil coke is used to reduce/remove the oxygen from the iron ore, is replaced by a process based on direct reduction with fossil-free hydrogen from electrolysis for the manufacture of sponge iron adapted for the production of crude steel in an arc furnace. The process will be scaled up in several stages with the commissioning of the pilot 2020 (approximately 4-5 MWel), demonstration plant in 2025 (approximately 400 MWel) accompanied by full-scale implementation by 2045 (up to approximately 11 TWh of electricity/7 TWh of hydrogen, corresponding to approximately 1300 MWel under the assumption of 65 percent electrolyser efficiency and 8,400 hours of operating time per year). When launching this strategy (January 2021), the localisation for the demonstration plant (Malmberget/Luleå) has not been decided yet. In the current pilot phase, materials and technology have been selected for a pilot (100 m^3) for an underground hydrogen storage facility, based on LRC technology (Lined Rock Caverns), whose construction is planned to begin in Luleå in early 2021. The storage facility can with advantage on a large scale (approximately 1,000 times larger than the pilot) be used, as a complement to hydropower, for significant balancing and regulating power for the electricity grid and at the same time reduce the total cost of steel production by adapting hydrogen production to the current electricity price. The potential climate benefit of applying the HYBRIT process at SSAB's plants is estimated at 1.6 tonnes of carbon dioxide per tonne of steel or on a full scale, about 5 million tonnes per year in Sweden. An additional 4 million tonnes of carbon dioxide per year can be cut if SSAB's blast furnace process in Finland is also replaced.

At the end of November 2020, LKAB announced how the hydrogen-based technology being developed within HYBRIT is now being taken further in one of Sweden's perhaps largest industrial adaptation projects of all time, corresponding to approximately SEK 10-20 billion per year for 15-20 years. The initiative is to completely phase out LKAB's production of iron ore pellets for the production of fossil-free sponge iron. Through this initiative, LKAB expects to be able to more than double its turnover by 2045 and thereby be able to meet both Sweden's needs and develop an important export product for the global market. At full scale, the process is estimated to require very large amounts of fossil-free electricity (about 55 TWh, out of which about 48 TWh for hydrogen production) as well as access to biofuel at competitive prices and rapid industrialisation of electrolysers to meet the needs of the initiative (1200 kton hydrogen, 7 GW, including HYBRIT's estimated capacity for 2045).[37]

Today, more and more steel companies are investigating hydrogen as one of several possible ways for their climate adaptation. For example, the German firm Arcelor-Mittal, one of the world's largest steel manufacturers, has recently announced that they will also invest in hydrogen with a first demonstration plant for direct reduction using hydrogen in operation in 2023 in Hamburg.[38] The steel manufacturer Voestalpine is also investing in adaptation of its steel production through hydrogen, but unlike HYBRIT and Arcelor-Mittal, they are investigating the possibility of reducing their climate footprint by replacing a larger proportion of the fossil coal and coke with hydrogen in the blast furnace process itself.[39]

Hydrogen for metal powder production:

Höganäs Sverige AB is now investigating the prerequisites for replacing in two steps the existing natural gas-based system for hydrogen production at its plant in Höganäs with technologies for the production of fossil-free hydrogen for its metal powder production. The technologies being investigated are hydrogen from biogas reforming, gasified biomass and electrolysis. The technology shift is planned to take place in two stages: in 2024 (corresponding to about 6 MWel if electrolysis), and 2030 (corresponding to a total of about 13 MWel if electrolysis). The studies are being conducted in collaboration with, among others, Cortus Energy (gasification of biomass) and the research institute RISE (Electrolysis).[40] The potential estimated climate benefit of replacing the fossil hydrogen, produced with existing fossil-based infrastructure, with fossil-free hydrogen in Höganäs corresponds to about 12,000-13,000 tonnes of carbon dioxide per year. If hydrogen through electrolysis becomes cheap enough to be used as fuel in the processes, hydrogen use would eventually become significantly greater at Höganäs (up to 50 MWel) and consequently also the potential for emission reduction (see the section "Hydrogen for steel heating" below).

Hydrogen as reduction agent in smelters:

The recovery of zinc is done today by reducing slag at high temperature at Boliden's smelting plant in Rönnskär. To achieve high metal yields during zinc recovery, fossil coal is used as a reducing agent and for the heat balance of the process. The use of fossil coal leads to significant carbon dioxide emissions. By replacing the fossil coal with hydrogen the climate emissions can be reduced. The conditions for replacing particulate carbon with hydrogen is now being investigated in a case study with Boliden and their smelting plant in Rönnskär in collaboration among others with RISE and Swerim.[40] The potential climate benefit is estimated to be at least 20,000 tonnes of carbon dioxide per year. Ammonia produced from hydrogen and nitrogen could be an alternative to hydrogen in this case. Ammonia is currently used as a reduction agent at the smelting plant in Rönnskär in the production of copper. An increased use of hydrogen for the reducing environment of metallurgical processes is also an interesting area, either as hydrogen or synthetic gas (synthetic gas mixture of carbon monoxide and hydrogen).

Hydrogen for heating steel:

By replacing natural gas or LPG with fossil-free hydrogen when heating steel, large climate gains and other societal benefits can be obtained. Ovako demonstrated the technology at full scale in March 2020, and the next step is to establish electrolysis modules of 16 MWel in 2022 provided funding is in place. The demonstration project has been run in collaboration with Linde Gas. At full scale (electrolysers in four Ovako locations, about 80 MWel) the fuel change has potential to reduce the carbon footprint by 100,000 tonnes per year for Ovako in Sweden, which today corresponds to 50 percent of the carbon dioxide emissions from Ovako's operations. The ambition is to share all relevant experience and technology with other companies that heat steel. Full implementation in Sweden could entail a centre of 50 electrolysers corresponding to approximately 800 MWel (about 4 TWh). These decisions can be made at the rate deemed appropriate and located in the strategically correct places. In total Ovako reports potential savings of about 1 million tonnes of carbon dioxide per year. The project has had a major impact globally and is considered a breakthrough in the industry with the potential to serve as a test bed for Sweden and a starting signal for spin-offs. Implementation of the technology is also expected to be able to contribute significant balancing and regulating capacity for the power grid, all the way down to split-second changes, while an important advantage is that the electrolyser's other product oxygen has local sales, which improves the cost efficiency of the adaptation. In this case, the economy also benefits from the fact that the surplus heat (and potential for flue gas condensation) can be utilised in district heating networks and the fact that most of the technology solution and infrastructure is already in place, including that no storage or distribution of hydrogen is needed.

In June 2020, Celsa Nordic, in cooperation with Statkraft and Mo industrial park in Norway, announced that they have similar plans to Ovako's to adapt their rolling mills.[41]

3.2. Examples in the energy sector

The electricity industry has described in its roadmap how they can enable increased electrification and thus fossil freedom in several sectors. With an increased share of renewable electricity production, several flexible solutions will be needed to balance the electricity system, where hydrogen is mentioned as a solution. The energy companies are often an important partner in the hydrogen projects launched because they are the first player in the value chain when turning electricity to hydrogen, before the hydrogen is used in any application. Electricity producers' interest in hydrogen is mainly based on gaining a market and thus increased value for their electricity production and includes parts of or entire value chains from electricity generation to hydrogen production, storage and use. In addition to this, there are possibilities to use the flexibility and control capacity of electrolysers and hydrogen storages to offer system services such as frequency regulation or to adapt electricity consumption patterns to prices on the electricity market.

For the purpose of frequency control and regulating power on the smaller scale, fuel cells have good technical potential at the same time as they generate heat that can be utilised in the cogeneration system. On the larger scale, hydrogen-powered gas turbines are also of interest in flexible production and power reserves. The latter are being developed by Siemens Energy in Finspång, for example, which is currently able to offer its customers gas turbine operation with 50–60 percent hydrogen gas in gas mixtures and aims to demonstrate 100 percent hydrogen operation on an industrial scale in 2030.[42]

From the perspective of the heat sector, it is mainly the utilisation of residual heat from hydrogen production and its use that is of interest.

The broad interest of energy companies is illustrated in several of the cross-sectoral partnerships initiated in recent years, such as Vattenfall's various partnerships with the Swedish process industry (examples are given in Chapter 3.1.1-3.1.2) or the newly established previously mentioned partnership between Liquid Wind and Ö-vik Energi. There are also other examples. Skellefteå Kraft is now investigating local large-scale hydrogen production and potential hydrogen customers in the surrounding area[43] and Rabbalshede Kraft plans to produce hydrogen from its wind power that will then be transported by road to industries.[44]

3.3. Examples in the transport sector

Sweden's target is to reduce emissions in domestic transport by 70 percent by 2030. To achieve this target, the automotive industry states in its roadmaps that electrification will play an important part. The industry will work to ensure that 80 percent of the sales of passenger cars in 2030 will be rechargeable and 50 percent of truck sales in 2030 will comprise electric trucks, but hydrogen is also highlighted as an important technology for long-haul transport. In the aviation industry's roadmap, the industry's target is that all domestic flights should be fossil-free in 2030 and all flights starting at Swedish airports fossil-free in 2045. The maritime industry's target is that domestic shipping should be fossil-free by 2045. Domestic transport accounted for 32 percent of Sweden's greenhouse gas emissions in 2019, with road transport accounting for by far the largest share of this.

Recently, hydrogen has had increased attention in the transport sector in various ways in Sweden, not least through the EU's hydrogen strategy and new partnerships in the heavy vehicle industry (AB Volvo and Daimler Truck). The regulations for reducing carbon dioxide for heavy vehicles are also pushing for zero emission solutions in the use phase.

With today's known technologies, the electrification of the transport sector can be done with hydrogen, batteries or electrified roads. All options have different operating cases that speak to their advantage. Direct use of energy when produced is always the most energy efficient, but the different operating cases combined with different factors such as energy density, ambient temperature, access to infrastructure and storage in the grid, business models etc. affect which solution is best suited to different applications. A probable development is that there will be a combination of the options mentioned.

Initiatives are underway in several areas around the world for hydrogen use in virtually all modes of transport, and development is fast, where priorities can change quickly when there are technological breakthroughs. Hydrogen can be used for all types of traffic, but much suggests that heavy road vehicles, trains and smaller passenger ferries become commercial in the medium term, while passenger cars and aircraft are expected to become commercial in larger volumes in the slightly longer term.

The role of hydrogen in the transport sector has undergone a number of different phases in recent decades with some periods of high political focus in different parts of the world. However, to date the use of hydrogen and fuel cells for transport is extremely limited.

The main reasons why hydrogen and fuel cells for transport have not yet reached the market on a large scale are the high total cost of fuel cell vehicles, including both the production of vehicles and the development of infrastructure with hydrogen fuel stations. Another slowing parameter is the relatively low energy density of hydrogen storage in both pressurised and liquefied form (almost 8 times lower energy density per unit volume at 700 bar than diesel), which contributes to less load capacity as the fuel tank is bulkier.

According to the Swedish automotive industry, the current increased focus on hydrogen in the transport sector has been promoted by several factors. One important driving factor is the development of renewable electricity production, including renewable hydrogen, in the EU. Another is that the lifespan of fuel cells has improved, which, together with the European development of hydrogen, makes hydrogen and fuel cells an interesting alternative for transport where electrification is otherwise difficult.

Compared to battery-powered vehicles, hydrogen enables rapid refuelling and provides a longer range for heavier vehicles, which requires fewer filling stations than for electric car charging, for example. One disadvantage is that the chain from electricity to hydrogen and then back to electricity in the vehicle gives relatively low system efficiency (about 30-50 percent). Thus, it is often more efficient if electricity can be stored via batteries. Hydrogen in combustion engines for vehicles is also a potential future area of application that is now being investigated in ongoing FFI projects (Strategic Vehicle Research and Innovation Programme, see Chapter 5.1). Hydrogen combustion engines have long been a known and possible alternative and they could be relevant for achieving zero emissions of carbon dioxide in the use phase.

Hydrogen can be an alternative in parallel with electrification with batteries and biofuels (for example HVO, biogas). For passenger cars and trucks used in regional transport up to about 300-400 km, electrification using batteries seems to be the central technology. Based on today's knowledge and prospects, hydrogen can play its role in the somewhat longer haul transport from about 300 to 800 km, while biofuels are probably used in all transport cases for existing vehicles, but with a focus on really long-distance and heavy transport in the long term. Hydrogen for passenger cars is not a primary focus for Swedish car manufacturers as electrification with batteries has higher priority. At a later stage, fuel cells could potentially be applied for range extension in electric vehicles as much of the technology is the same for fuel cell vehicles and electric vehicles.

Technology transfer today is from passenger cars to heavier vehicle types, such as Toyota Mirai's stacks being used in Project Portal in the Port of Los Angeles, where trucks are fitted with double stacks from the passenger car side. The same technology transfer is seen from light trucks to heavier trucks.

In the long run, the use of electrofuels may be of interest to the automotive industry (road, aviation, shipping), as a complement to biofuel.[45] The advantage is that most electrofuels, unlike pure hydrogen, are compatible with existing infrastructure and that there are alternatives such as electromethanol that is liquid at room temperature and thus easier to store and transport. One disadvantage is that electrofuels will always be more expensive to produce than hydrogen (from about 10-50 percent depending for example on electricity price, choice of technology and product[46]) since the production process itself requires more process steps but in return management and storage is easier. Another disadvantage of electrofuels is the very low system efficiency (approximately 10-20 percent from electricity to hydrogen to electrofuels for conversion in a combustion engine[47]). Development is also taking place internationally regarding the use of hydrogen in trains with fuel cells. For example there is already a fuel cell train from the French company Alstom in service in north-eastern Germany and in November 2020, Siemens announced that they intend to produce fuel cell powered trains in cooperation with Deutsche Bahn. The Swedish rail network is largely electrified, but there may be a possibility for the routes where diesel locomotives currently operate. Examples of routes currently under investigation for fuel cell-powered trains are the Inlandsbanan between Mora and Gällivare and Kinnekullebanan.

Another current application is in aircraft, where historically it is very difficult to find alternatives to the strictly safety-controlled liquid fuels used. The concept of hydrogen-powered aircraft has been presented on several occasions in the past. During the autumn, Airbus presented three different concepts for future aircraft, powered by the combustion of liquid hydrogen in gas turbines, with the aim of producing a first plane by 2035. In the UK an early plane was flown by Zeroavia using fuel cell technology from Swedish PowerCell. The use of hydrogen for international aviation is expected to be relatively far in the future, but it is important that Sweden and Swedish actors are involved in the development of short-haul flights up to 1,000 km (Airbus and others). The aircraft engine manufacturer GKN in Trollhättan has a strategically important role in this development.

Shipping is also facing major challenges in the transition to the use of sustainable energy for propulsion and auxiliary systems. Shipping has special challenges compared to other modes of transport, such as long service life, high energy consumption, various operating profiles and an often international movement pattern. At the time of writing, there are several different fuels and powertrains that are more or less relevant, electrification using batteries, methanol, ammonia, HVO, LBG, hydrogen and electrofuels. It is likely that a certain type of energy will be an option for some vessels but not others, which means that a total solution may be difficult to achieve. Hydrogen and fuel cells can find their place both as energy for propulsion but also as energy to the auxiliary systems on board. There are some minor initiatives around the world that are ongoing. In Norway, for example, larger installations are now being built to be made operational in 2022. In 2020, a feasibility study funded by the Lighthouse maritime programme will be carried out by RISE and Svenskt Marintekniskt Forum aimed at simulating an after-installation of a hydrogen fuel cell powertrain on board Rederi AB Ventrafiken's ferry Uraniborg.

3.4. Examples in agriculture and food

The target of the agricultural industry's fossil-free competitiveness roadmap is to become 100 percent fossil-free on fuel, drying and heating in 2030. In the long term they intend to phase out the use of mineral fertilisers produced with fossil fuels. In 2019, the food and agricultural sector accounted for 14 percent of Sweden's greenhouse gas emissions.

In agriculture, hydrogen is mainly used for the production of mineral nitrogen fertiliser. All nitrogen fertilisers used in Sweden are based on ammonia, which is produced in the so-called Haber-Bosch process where hydrogen and nitrogen gas are synthesised. The hydrogen used in the fertiliser industry is now manufactured from natural gas, coal and oil. There is very little ammonia production and mineral fertiliser production in Sweden. Instead, the industry imports from Germany, Holland, Norway and Russia.

Nitrogen fertiliser production (2.0 TWh) is the second largest fossil energy input in Swedish agriculture after diesel for working machinery (2.4 TWh)48. The food industry is thus dependent on fossil resources, and domestic production of fossil-free hydrogen to produce mineral nitrogen would be a key to a secure independent food system without fossil energy, and thus constitutes a piece of the puzzle in the transition of agriculture and society as a whole.[49]

The total amount of nitrogen in the mineral fertiliser sold in Sweden today amounts to about 183,000 tonnes per year.[50] To produce 1 tonne of nitrogen in nitrogen fertiliser, 0.21 tonnes of hydrogen is needed. To provide the whole of Sweden's agriculture with nitrogen fertiliser, approximately 40,000 tonnes of hydrogen would be needed annually. If all nitrogen fertilisers in Sweden were produced using fossil-free hydrogen, about 1 million tonnes of carbon dioxide equivalents could be saved, which are currently emitted in other countries, which corresponds to about 7 percent of Swedish agriculture's climate emissions (from a broader perspective than the agricultural sector in the climate reporting) and 2 percent of Sweden's national climate emissions. These estimations are based on the assumption of approximately 0.1 kg carbon dioxide equivalents/kg green nitrogren[51] and 4.5 kg carbon dioxide equivalents/kg fossil nitrogen (i.e. mean value based on data from Statistics Sweden in 2020).

The Danish energy company Ørsted and plant nutrition industry manufacturer Yara announced in October 2020 that they are planning to establish the world's first demonstration plant for the production of renewable ammonia (75,000 tonnes of ammonia per year). The plant, which is supplied with hydrogen from electrolysis (100 MWel), is planned to be established in the Netherlands and is expected to have the investment decision in place in 2021/2022.[52] In September 2020, Yara announced that they had also initiated a partnership with Swedish Lantmännen in order to develop a pilot project aimed at creating the world's first certified food chain with fossil-free mineral fertiliser on the market in 2023.[53] On the initiative and driven by Invest in Norrbotten, discussions are also underway with various parties for the development of Sweden's first facility for large-scale production of ammonia and mineral fertilisers from electrolytic hydrogen and nitrogen. LKAB is also investigating the possibilities for large-scale fossil-free mineral fertiliser production in the feasibility study ReeMAP.[54]

The agricultural sector is also showing increased interest in decentralised hydrogen production from wind and/or solar power in order to become a self-sufficient farming system, where, in this case, renewable hydrogen, in addition to locally produced biogas, can be used for farm operations. This includes fuel as well as working machinery. For example, LRF Gotland has conducted a preliminary study on the possibilities of producing and storing hydrogen on a small scale at farm level, including various hydrogen applications, and is now investigating the possibilities for establishing pilot plants.[55]

3.5. Examples in the construction and real property sector

The target of the construction and civil engineering sector's road map for fossil-free competitiveness is for the construction value chain to achieve 50 percent reduction in emissions by 2030 and fossil freedom by 2045.

The construction and real property sector is a sector in which decentralised hydrogen production (equivalent to orders of magnitude from a few to a few hundred kWel) can play a role as part of the development of self-sufficient buildings and sustainable cities and communities, called off-grid (in continuous operation) or island operation (for temporary operation). The sector is also showing interest in decentralised hydrogen production as part of creating electricity grid benefits (not off-grid).

The off-grid concepts in the construction and real property sector are usually based on combinations of technologies, where small-scale renewable intermittent electricity production, electrolysis, hydrogen storage, fuel cells, local heat production and batteries are combined.

Island operation with hydrogen is of particular interest for purposes where it is critical to have electricity supply if the power grid cannot deliver for any reason. Hospitals, water supply and sewage facilities or other sensitive buildings where it is important to have some kind of backup power supply can be potential customers for hydrogen. Properties with island operations can also be used in crisis situations, for example as staff headquarters and command posts for municipalities' crisis organisation or other critical activities that may not be closed down. Instead of having backup based on diesel or other fossil energy, fuel cell technology can in this case provide a quiet and renewable energy source. Together with other renewable alternatives such as biogas, biodiesel and electrofuels, which may be relevant for this purpose, the advantage is also a reduced dependency on imports, given that there is robust production in Sweden.

There are currently a number of projects and initiatives in Sweden in the area. One example is the Swedish Post and Telecom Authority, which is conducting a study on using fuel cells as reserve power for electronic communications. Additional examples are Hans-Olof Nilsson's off-grid house outside Gothenburg, Skellefteå Kraft, which built the concept villa Zero Sun that stores solar energy in the form of hydrogen and the housing company Vätterhem's plans to build 44 apartments in two self-sufficient buildings in Jönköping with energy systems that include solar power and hydrogen storage. In connection with off-grid solutions of this kind, a filling station for hydrogen vehicles can also be included with hydrogen supplied from the decentralised system's electrolyser.

3.6. Overall picture of milestones, magnitudes and potential carbon gains

Figure 9 presents an aggregated picture for the more concrete plans and projects described above. Note that not all projects have decided whether the hydrogen shift will take place via electrolysis. As described in the previous section, in some cases it may be a mixture of hydrogen from electrolysis, gasification or reforming of biomass and/or blue hydrogen.

The total need for hydrogen for these projects is 50 TWh, where 45 TWh is needed in projects focusing on hydrogen via electrolysis, which in this case corresponds to a need for 55 TWh of electricity.

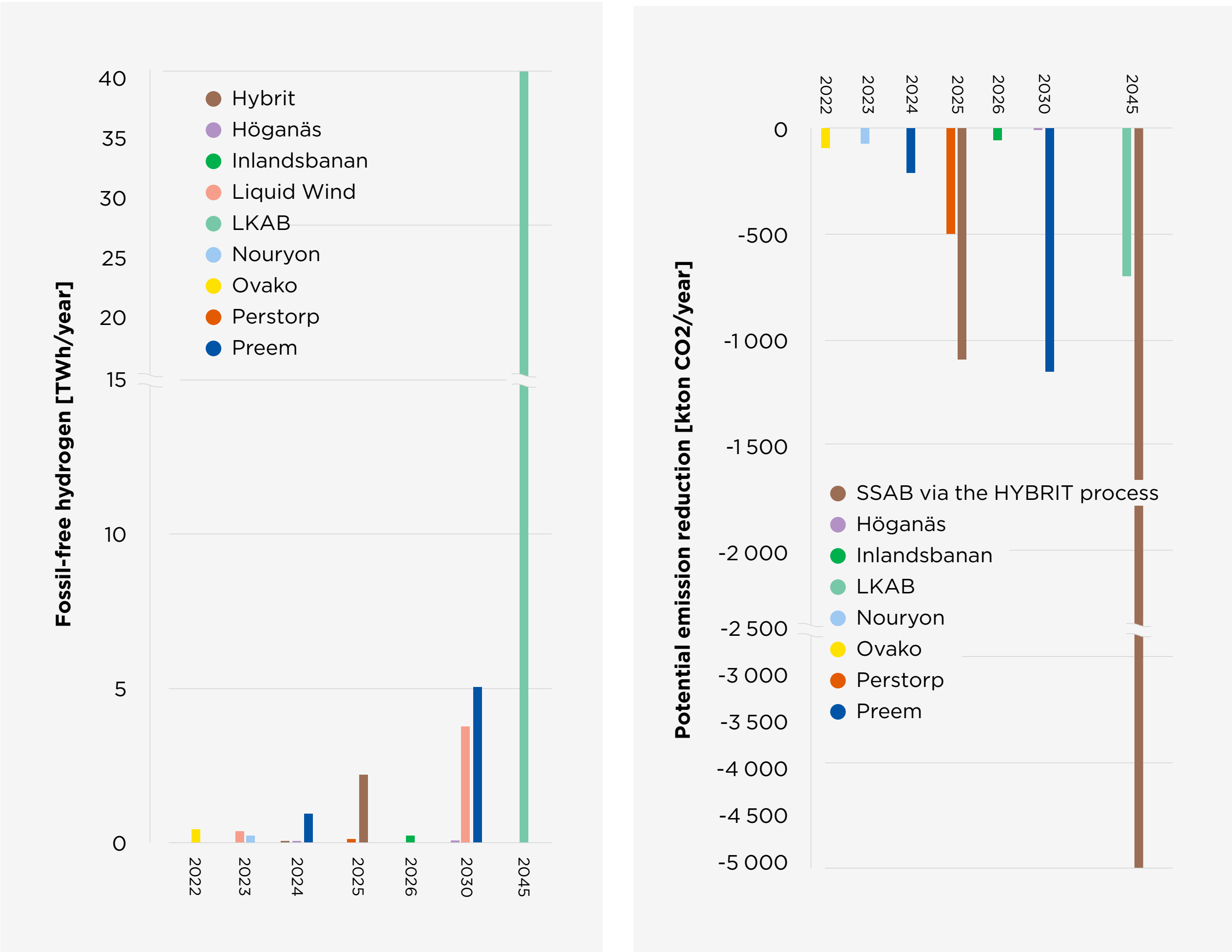


Figure 9: Timeline showing aggregated milestones, magnitudes and potential carbon dioxide emission gains for the more concrete current plans and projects in Sweden. The estimated amount of fossil-free hydrogen is under the assumption of 65 percent efficiency for electrolysers and 8,400 hours operating time per year unless otherwise indicated by the industry. Only direct emission reduction is included in the figure, additional potential exists in the user phase. Please note: 1) In several cases, the total outcome of the projects will not emerge at one and the same discrete time (for example LKAB and SSAB's transitions) but instead be ramped up in stages (where development rates had not been announced at the strategy's publication in January 2021). 2) Preem and Höganäs have not determined that fossil-free hydrogen is to be produced via electrolysis. Furthermore, Preem has not decided how their hydrogen balance is to be provided in 2030, a mixture of electrolytic hydrogen, hydrogen from biogas and blue hydrogen is likely.

The potential for emission reduction depends on what the hydrogen gas replaces, which differs between different applications, for example replacing coal as a reduction agent in steel production, natural gas in the production of hydrogen through reforming, various fossil fuels in the transport sector, and fuels in combustion in industrial applications. The estimate of potential emission reduction in Figure 9 is based on information from relevant Swedish industries.

The projects in Figure 9 are estimated to have the potential to reduce carbon dioxide emissions by 7,100,000 tonnes, which corresponds to about 14 percent of Sweden's national emissions in 2019, when only direct emission reduction is included. For several of the projects, the greatest potential for reduced emissions is in the user phase and among customers. This is discussed in the paragraphs below.

For Preem, only the reduction of emissions on-site at refineries is included in these bars. However, the largest emission reduction occurs in the user phase, i.e. where the fuel is combusted. Plans for increased production of biofuels by 2024 are estimated to result in emissions reductions of 1,700,000 tonnes of carbon dioxide per year throughout the user phase, which is almost 8 times as much as is reported for the plant in Figure 9. If the emission reduction in the user phase for biofuels is included, according to plans for 2030, and the reduced emissions from agriculture that hydrogen to nitrogen fertilisers can contribute to the figures in Figure 9, the total reduction will instead be just over 31 percent of Sweden's national emissions in 2019.

For Liquid Wind, there is no emission reduction in the figure, but they state that their ten plants will be able to capture 700,000 tonnes of carbon dioxide per year for a methanol production of 500,000 tonnes per year. The carbon dioxide captured during production is then released on consumption of the fuel, meaning that it does not cause any net emissions of carbon dioxide. How the capture and use of carbon dioxide should be handled within the EU ETS is being updated, as described in Chapter 2.3. Based on existing EU legislation within the EU ETS and RED II, however, it is clear that double-calculation of carbon reduction will be avoided and that carbon dioxide included by the EU ETS should burden the industry in which it was captured. However, an emission reduction is achieved in the user phase by replacing fossil petrol and diesel, which is estimated to save 2 tonnes of fossil carbon dioxide per tonne of methanol. In total, the emission reduction for the planned production of methanol will be 1 million tonnes per year, which corresponds to 2 percent of Sweden's national emissions in 2019.

Perstorp has estimated the carbon dioxide reduction for "Project Air" to be 500,000 tonnes per year for the entire project. The methanol to be produced will meet the needs of Perstorp's European plants. The estimate includes both emissions reduction in the Swedish plant, as a result of the new production process for methanol, and emissions reduction at end-of-life for the products produced from methanol in Europe. For this reason, the figure has not been included in Figure 9 but overall, the project's emissions reduction corresponds to 1 percent of Sweden's national emissions in 2019.

For Inlandsbanan, the potential for emissions reduction when switching to hydrogen operation is based on diesel consumption for train traffic on the track today. According to Inlandsbanan itself, the project can also release capacity on the Northern main line and the main line, which in turn can contribute to reduced road transport and thus further emission reductions. However, these potentials have not been estimated or included in figure 9.

In addition to Inlandsbanan, there are current projects to change Kinnekullebanan from diesel operation to hydrogen operation.

For LKAB's part, only the reduction of the company's emissions from production have been included in Figure 9. However, in the transition to the production of carbon-free sponge iron, of the largest part of the emission reductions take place at LKAB's customers in the Swedish and international steel industry. The company has estimated that the reduction totals 35 million tonnes of carbon dioxide per year, which corresponds to two thirds of Sweden's territorial emissions.[32] Of the emissions reduction in the customer chain, 5 million tonnes are in Sweden via the HYBRIT process in SSAB's facilities, included in the figure above, and the remaining 30 million tonnes are abroad.

Table 1 summarises hydrogen needs and emission reduction in Sweden as described in the text above. It also shows the installed electrolysis power for the announced projects. Note that emissions reduction from Perstorp's "Project Air" and Liquid Wind's planned production is not included, these together correspond to 3 percent of Sweden's national emissions.

By adding to the announced plans above (50 TWh) the need to replace the remainder of today's use of fossil hydrogen (about 0.6 TWh), the increased need for hydrogen for the stated plans for the production of biofuels (about 8 TWh) and potential hydrogen use in new value chains (about 3 TWh), an estimate is obtained of the total hydrogen requirement of 61 TWh in 2045. If all this hydrogen were to be produced via electrolysis, approximately 81 TWh of electricity would be required in 2045, which is almost 3 times the wind power produced today (28 TWh, 2020) and half of the total electricity production (164 TWh). [56]

The figure of 81 TWh of electricity is interesting to illustrate the orders of magnitude involved, but since electrolysis is unlikely to be the only production technology to meet Sweden's future need for hydrogen, the estimated potential of future installed electrolysis power must be based on other assumptions. One approach is instead to start from the total installed power of the plans stated at the time of writing via electrolysis (Table 1) and add additional power that it is reasonable to expect via plans that are currently not yet known. Taking into account Sweden's climate goals, the number of major investments announced only in recent months, and the relatively large opportunities for public funding now being made available in the area (see Chapter 6),

Year	**2030**				**2045**			
	TWh_{H2}	**MWel**	**ktonne CO_2**	**Share of national emissions**	**TWh_{H2}**	**MWel**	**ktonne CO_2**	**Share of national emissions**
Projects with hydrogen via electrolysis	7	1280	235	0,5 %	45	7880	5937	11,7 %
Projects where several production technologies may be included (Preem and Höganäs)	5	936	1 167	2,3 %	5	936	1167	2,3 %
Delsummering	12	2217	1402	3%	50	8817	7104	14 %
Transition to nitrogen fertiliser based on fossil-free hydrogen			1000	2 %			1000	2 %
Reduction in user phase (Preem)			7 794	15 %			7 794	15 %
Total			10 196	20 %			15897	31 %

Table 1: Summary of hydrogen needs, electrolysis power and emission reduction for announced projects, both where electrolysis is explicitly the intended production technology, and where several alternatives are evaluated. To this is then added the potential for emission reduction when transforming into fossil-free hydrogen for the production of fossil-free nitrogen fertilisers and the emission reduction in the user phase for Preem, as it is evident that this fuel will be used in Sweden.

it is reasonable to expect that plans corresponding to an additional 50 percent of installed electrolysis power will be added to the currently known plans for 2030. A range for the probable total installed electrolysis power for the same year in Sweden can be estimated, where the minimum level corresponds only to those plans with decisions on electrolysis while the maximum level also includes the plans where other manufacturing technologies are now being investigated. Since 2045 is considerably further away,the total hydrogen demand for projects that have chosen the production technology is set as an estimated value for for installed electrolysis power (8 GWel, see Table 1). With these assumptions, it can be noted that the estimate for 2045 requires approximately 63 TWh of electricity, which corresponds to about 40 percent of total electricity production in Sweden in 2019 (164 TWh). The results of the potential estimate for 2030 are listed in Table 2.

To be able to evaluate the reasonableness of potential estimates given here, in this case a comparison can be made with the rate of expansion for wind power in Sweden. The annual production rate for Swedish wind power increased by 8 TWh from delivering 20 TWh in 2019 to delivering 28 TWh in 2020, corresponding to an expansion of 40 percent of total production in one year. With continued technical development, using higher towers and larger rotors on the wind turbines, this development will continue. Svenska kraftnät's (Swedish transmission system operator) short-term market analysis[57] indicates 36 TWh in 2021 to 50 TWh in 2025. In the longer term, the Swedish Wind Energy Association indicates 90 TWh of wind power production in 2040[58] and the Swedish Energy Agency's main scenario[59] indicates 80–120 TWh new renewable electricity production in 2045 in Sweden.

The geographical distribution of future projects concerning fossil-free hydrogen is illustrated in Figure 10. This also shows that the majority of the projects intend to use electrolysis as production technology (marked green). Note that only one of Liquid Wind's ten planned facilities has been included in the figure, since they have only announced this location. The first plant is, as mentioned in Chapter 3.1.1., planned for Örnsköldsvik, adjacent to Ö-vik Energi's combined heat and power plant, while the remaining nine will be located in Scandinavia, near industry with major biogenic carbon dioxide emissions (pulp- and paper industry, co-generation industry). In addition to the projects on the timeline above, the map also includes a project for fuel replacement for Borealis Kracker. In this transition, hydrogen is not the only measure examined but also direct electrification or a combination of the two.[35] For this reason, the project has been marked in a different colour than the others. Inlandsbanan has been marked as a dot on the map, but

Year	2030
GWel min	1,9
TWhel min	16
GWel max	3,3
TWhel max	28

Table 2: Potential estimation of installed electrolysis power (MWel) and corresponding amount of electricity (TWh electricity) in 2030 in Sweden, which forms the basis of the planning goals in the Action Plan. The potential has been estimated as follows:

- (2030, min) – (total power for known projects using electrolysis) X 1.50
- (2030, max) - (total power for known projects using electrolysis + total power for the known projects that have not yet decided on production technology) x 1.50

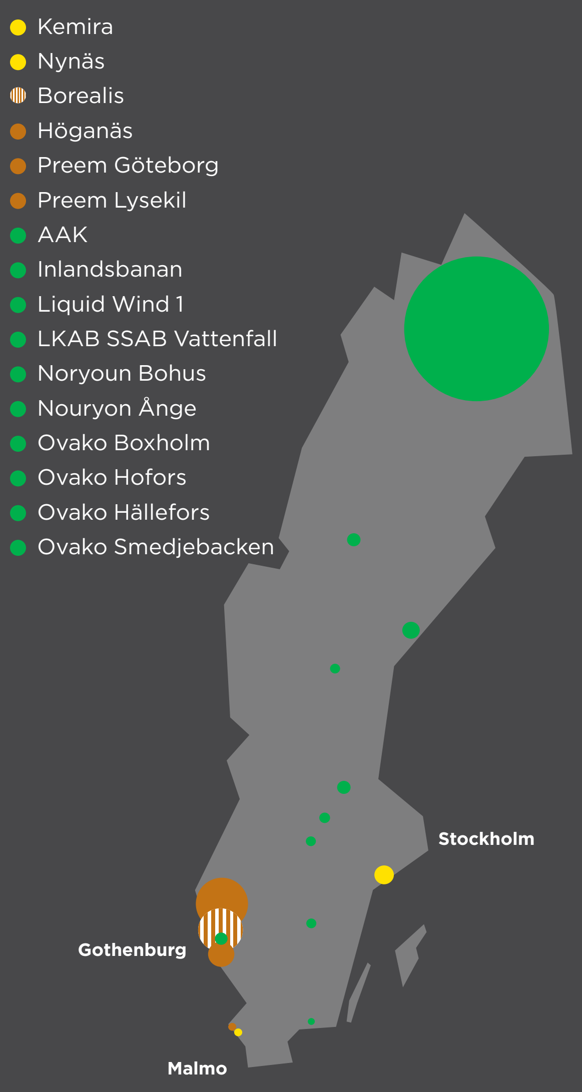


Figure 10 : Future hydrogen production and use in Sweden. Projects focusing on fossil-free hydrogen via electrolysis are green, a mixture of fossil free hydrogen (not only from electrolysis) and blue hydrogen are brown, the projects where not only hydrogen is relevant are brown-striped and those marked grey on the map have no stated plans for the transition from fossil hydrogen. Please note that for simplicity, future hydrogen needs when converting via the HYBRIT process at LKAB and SSAB are shown as a point, though the location of the demo facility had not yet been decided at the time of publication of the strategy in January 2021 (Malmberget/Luleå).

the route is from Gällivare in the north to Mora in the south. The original route also included tracks from Mora down to Kristinehamn, but now that part is managed by the Swedish Transport Administration.

3.7. Infrastructure and sector coupling between existing and new value chains

3.7.1. Hydrogen development through developing industrial clusters

The concept of hydrogen infrastructure includes the production, storage and distribution of hydrogen. In Sweden today, where virtually all hydrogen is produced close to where it is used, there is no infrastructure of note available for the storage or distribution of hydrogen.

Distribution through grids is today the most cost-effective way of transporting gas over long distances. In view of the cost per energy amount transported, some studies indicate that the cost is approximately the same or even cheaper to transport hydrogen in gas pipelines than transporting the same amount of energy via the electricity grid.[60,61] As regards hydrogen pipelines in Sweden, however, these are limited to a few local grids in industrial areas (such as the Stenugnssund cluster, Höganäs industries in Höganäs, Sandvik Materials in Sandvik, Kemira in Helsingborg). Hydrogen distribution in Sweden today is instead exclusively by road in compressed form. For the distribution of larger hydrogen volumes over medium to long distances by road, it is usually cheaper to transport hydrogen in liquid form, but since so far there is no market, this is not yet done in Sweden. Furthermore, so far there are only a few small (storage at filling stations) and medium-sized hydrogen storage facilities (for example, Höganäs AB's industrial area in Höganäs). This poor availability of both hydrogen storage and distribution is something that many actors in both the industrial and transport sectors point out as one of the biggest obstacles to ambitious hydrogen development in Sweden.

One way to accelerate the development and expansion of associated hydrogen infrastructure around the country is to establish cross-sectoral local and regional hydrogen clusters where existing major industries and infrastructure such as ports, railways, etc. already have or will be able to use hydrogen. It would thus be an establishment of what the EU strategy calls a Hydrogen Valley (see chapter 2.3.1).

In Sweden, cluster development for hydrogen is already under discussion in various places, including on the west coast from Gothenburg via Stenungssund to Lysekil and in Gävleborg and Dalarna (e.g. Gävle – Sandviken – Hofors). The Västra Götaland region is working on such a vision, and Gävleborg and Dalarna has recently established a so-called hydrogen council for increased coordination between regional businesses, academia and public organisations. Based on the various initiatives and larger projects that are now underway in Sweden, it is also reasonable to expect future cluster development in Norrbotten and Skåne (Höganäs – Helsingborg), Figure 11. There are also other examples of regions in Sweden, which are not shown on the map in Figure 11, where hydrogen development through local and regional clusters is now being discussed. One example is Jämtland, where the cluster idea is based on Jämtkraft's ongoing preliminary study on the production of synthetic aviation fuel in combination with Inlandsbanan's transition to hydrogen operation.

Through cluster development, cross-sectoral partnerships and commerce platforms can be created, where existing and new industries can be linked together with local and regional hydrogen networks and/or common hydrogen storage facilities. Furthermore, economies of scale can be obtained as hydrogen can probably be produced at more competitive prices through the installation of large electrolysers, but also by combining new infrastructure for hydrogen production with infrastructure that already exists in some places for electricity or production of hydrogen from other sources so that the fossil share is phased out over time. In cases where common infrastructure is utilised for hydrogen produced with different technologies and/or from different input materials, product quality standards need to be reviewed, since different applications require different demands on purity. Additional costs that arise as a result of any necessary gas cleaning also need to be taken into account. Another question to clarify is how renewable hydrogen should be accounted for when gas is exchanged in a common system.

Another interesting future opportunity is to combine new hydrogen infrastructure with infrastructure for carbon dioxide for electrofuel/electrochemical production, for example in Gothenburg, where techno-economic conditions for regional carbon dioxide infrastructure are

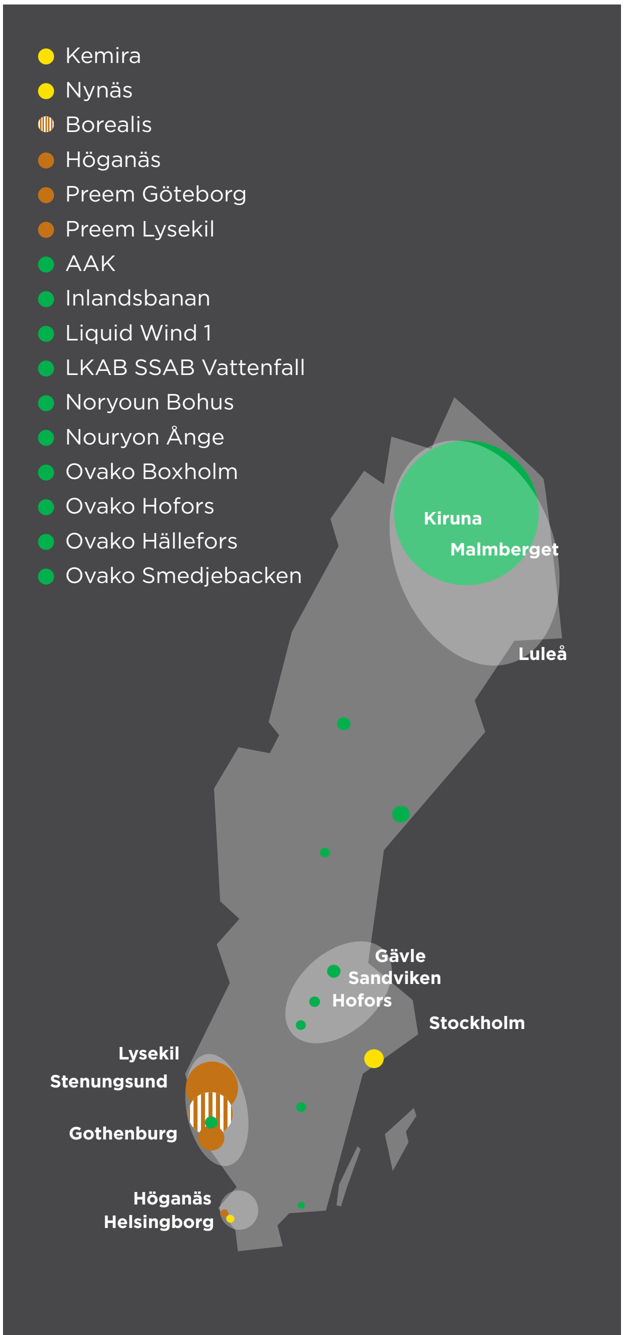


Figure 11 : Examples of potential hydrogen clusters in Sweden illustrated on the basis of the more concrete plans and projects in Sweden described in Chapter 3 and marked in Figure 10. Since the location of the HYBRIT demo facility had not yet been decided at the time of the strategy's publication in January 2021 (Luleå/Malmberget), Luleå is also marked on the map.


H2
HYDROGEN
ENERGY
STORAGE
H2

now being investigated within the framework of the project "CinfraCap".[62] Since the electrolysis process or thermochemical production of hydrogen from biogas also generates heat, proximity to district heating networks also gives synergy effects (see Chapter 3.7.2).

Cluster development is also run in some locations for logistics reasons. For example, cities with ports, such as Gävle harbour, have an interest in ensuring that transport within the port as well as even to and from the port are emission-free and can thus strengthen the cluster investment.

As mentioned in Chapter 3.3. there are clear advantages in placing so-called strategic filling stations close to the larger industries within the clusters. There is already an ongoing dialogue between the basic industries and vehicle manufacturers about establishing a station structure for hydrogen for heavy road traffic. In the even longer term, it is also of interest to establish infrastructure for both compressed and liquid hydrogen at airports.

The development of hydrogen infrastructure through industrial clusters in Sweden can be complemented in some parts of the country through ongoing initiatives such as Inlandsbanan, which can constitute freight corridors for the transport of hydrogen over long distances.

A future scenario, which is presented in the report "European Hydrogen Backbone" by European gas grid owners (see 2.3.1.), is that certain clusters in Sweden could then be linked over time with new long hydrogen pipelines complemented by maritime, rail and road transport, which in the long term will also be linked to the rest of the Nordic area and Europe. In this strategy, this scenario is not assessed as realistic, as it is based on the existence of a larger network of disused natural gas pipelines that could be converted to hydrogen networks, which is not the case in Sweden.

However, investigations on linking small nearby clusters with each other through new hydrogen pipelines, as well as on centralised compared to decentralised hydrogen production via electrolysis, are relevant in Swedish contexts. In this case, the question concerns whether large-scale hydrogen production is more cost-effective in a location with good access to electricity, including distribution of gas over longer distances, in comparison with decentralised production at a location where the electricity grid may instead need to be reinforced. Although the forecast of rapidly falling prices for electrolysers favours decentralised hydrogen production, in this comparison it is also necessary to consider any need for hydrogen storage with regard to both function and cost, so that the solutions are cost-effective overall. The answer is thus not given and probably something that needs to be both investigated and tested more closely for different localisations in Sweden, as the conditions differ both in terms of infrastructure for natural gas and biogas, electricity supply, storage and distribution, etc. The West Swedish chemical and material cluster in Västra Götaland is now working to initiate a feasibility study that aims to investigate this with regard to the regional industries' hydrogen needs, timetable and possible limitations in the electricity grid. Similar issues, from a Nordic perspective, are now also being investigated in the study "Nordic Clean Energy Scenarios". [63]

3.7.2. Sector coupling opens up for valuable synergies

As the need for hydrogen is cross-sectoral, there are great opportunities for synergies (Figure 12). By coordinating initiatives across sectoral boundaries, large profits for individual actors as well as society, the climate and the environment can be obtained:

- **Economies of scale and shared risk-taking for new infrastructure.**
  By establishing the cross-sectoral local and regional hydrogen clusters described above (see 3.7.1), hydrogen can be produced, distributed, stored and used in larger volumes for more cost-effective total solutions. Within the clusters, joint infrastructure can be established, where risk-taking and investments are shared between several parties and industries.

- **Better profitability by using the by-products of the electrolysis process.**
  In addition to hydrogen, the electrolysis of water also produces heat and oxygen. Where the by-products can also be utilised, either locally or sold to another party on an external market, better profitability for the individual plant or industry can generally be achieved. The residual heat from the electrolysis (equivalent to about 20 to 35 percent of energy supplied) is produced continuously during operation

and can therefore be utilised for heating or cooling of the premises where the electrolyser accounts for production of district heat (see, for example, “Hydrogen for steel heating” under 3.1.2) thereby releasing biomass used in biopower plants for other higher-grade products. As it involves relatively low temperatures (50-80 °C, depending on the type of electrolyser), heat pumps may be needed for efficient use of residual heat. The oxygen produced can in some cases replace and simplify parts of the industries’ existing oxygen infrastructure, such as in steel and smelting plants and pulp mills. The oxygen can also be used for example in fish farms or in water treatment plants in an industrial symbiosis if they are nearby, or alternatively for oxygenation of the sea bottom.

- **Increased flexibility and balancing of output in the electricity system.**
  Hydrogen produced by electrolysis enables energy storage over time and of much larger amounts than, for example, batteries can achieve. Combinations of hydrogen and batteries open up for storage from parts of seconds to storage over days, weeks and months, thus providing both flexibility of services for short time horizons (such as frequency or voltage regulation) and balancing over longer periods of time. Several projects are currently underway in Sweden that are investigating the latter in combination with decentralised power production and hydrogen filling stations. For example, Swedish system integrators, such as Nilsson Energy and Euromekanik, are working on the development of green decentralised hydrogen solutions for mobile and stationary systems, in which reserve power and power balancing are parts of the system solution.

Also the process industry with large-scale hydrogen production will probably be an important player in the future energy market. This can be done in different ways through electrolysis in combination with other new and/or existing infrastructure. One example is Höganäs AB with its existing medium-sized hydrogen storage facility. Another example is the good future potential for the HYBRIT process to contribute with both flexibility and power balancing up to several days (approximately 100 GWh, equivalent to approximately 1 million Tesla cars) through its large-scale hydrogen production combined with underground hydrogen storage facilities where hydrogen production and thus electricity needs are adapted to the prevailing electricity supply and price. One example of where new infrastructure is combined with existing infrastructure is Ovako’s planned studies to be able to contribute to network stability without any intermediate hydrogen store. In their case, fossil-free hydrogen is to be generated at the rate it is consumed and contribution to network stability can be achieved by switching between fossil gas (reserve) and hydrogen systems. Another example is refineries that point to their future opportunities to contribute with both power and flexibility services by linking and utilising existing infrastructure for production of hydrogen from natural gas/biogas with fossil-free hydrogen from electrolysis.

- **Synergies with offshore wind power.**
  The costs of offshore wind power are falling rapidly and the large electricity production in offshore parks creates great potential for hydrogen production. Around the world there are ongoing or planned projects where offshore wind power is integrated with hydrogen production. One example is Siemens Gamesas pilot project[64] in Denmark where hydrogen can be produced either directly from wind power in “island operations” or with connection to the electricity grid. In Sweden, the Government has recently submitted proposals to reduce the connection costs for offshore wind power,[53] which could help to make offshore wind farms around Sweden’s coasts a reality. Connection points for offshore wind power and the grid reinforcements also mean that the capacity for producing hydrogen can increase. Another possibility is to establish floating wind turbines in the oceans outside of potential hydrogen clusters.

- **Increased exchange and possible substitution of biomaterials.**
  In the production of biofuels/biochemicals at a biorefinery, a variety of biomass carbon atoms end up in products, but for many techniques the carbon efficiency is relatively low. In the longer term, biomass conversion and utilisation techniques are expected to have high carbon utilisation and/or enable negative emissions to be legitimate and competitive. By combining electrolysis for fossil free hydrogen production with various process methods for biofuel

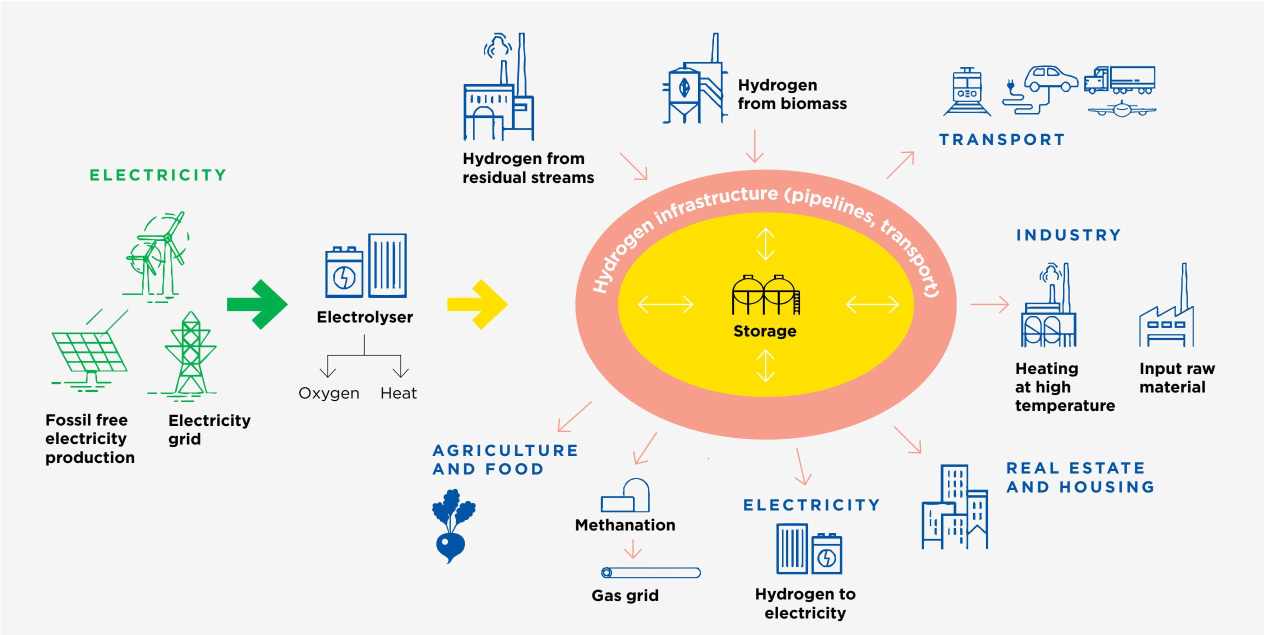


Figure 12: Hydrogen value chains, which are taken into account in this hydrogen strategy.

production, both carbon and climate efficiency can increase for entire value chains. Carbon efficiency indicates the proportion of carbon that is bound in and is made use of in desired products, such as biofuels or negative emissions compared to the total amount of carbon in the biomass raw material. In many cases, it is possible to achieve close to 100 percent carbon efficiency, which means significantly improved resource efficiency. This type of hybrid between bio- and electrofuels is now being evaluated by the RISE research institute and Luleå University of Technology in collaboration with several industrial partners[65] and has also been studied by the VTT research institute.[66, 67] These types of production processes are generally not commercial today, but may play an important role in the longer term in order to reduce the climate impact of both transport and industry and contribute to the transition to the renewable energy system and a more resource-efficient society.

4. Technology and sub-contractors

The conversion to hydrogen creates a strongly expanding market where Sweden has the opportunity to develop its industry and role in both domestic and global export markets. An important part of this industry concerns technology and subcontractors.

In contrast to, for example, Norway and Denmark, there are no Swedish companies today that develop and sell complete electrolysis systems. However, there is an industry on the rise in Sweden for technology and subcontractors in the area, most of which are global players. Examples are Sandvik Materials Technology, which has many years of experience in material development for the hydrogen industry and which, among other things, develops components in fuel cells. Others are Permascand, which develops components for industrial alkaline electrolysers, Höganäs, which is a subcontractor to manufacturers of electrolysers and fuel cells (high-temperature) and Alfa Laval that works in various ways to improve the efficiency of heating and cooling processes for both production and application areas for hydrogen. Further examples include previously mentioned Siemens Energy in Finspång, which develops and sells industrial gas turbines where hydrogen can be used as fuel, as well as PowerCell, which develops fuel cell systems for transport, maritime and stationary applications.

In Sweden there is also a number of smaller technology and system suppliers active in the hydrogen field. One example is Plagazi which develops plasma technology for production of hydrogen from organic waste, which now together with the municipality of Köping, is building its first facility, including CCS, as a replacement for the current waste incineration plant. Other examples are Impact Coatngs which manufactures flow plates for fuel cells and Celcibus which develops platinum-free catalysts for fuel cells. Companies that with the right prerequisites have the opportunity to develop into important building blocks in Swedish industry.

5. Research, development and competence supply in the hydrogen field in Sweden

5.1. Ongoing research and development

The majority of industrial development projects for new value chains with hydrogen include research partnerships with several Swedish universities and research institutes. Technology and system suppliers also participate in many of the projects. The activities cover entire value chains, from the development of individual materials and system components, process steps, process integration to system analysis and policy, and are carried out with the support of, among others, the Swedish Energy Agency.

To facilitate networking, knowledge transfer and initiation of new projects and cross-sectoral partnerships, a number of initiatives such as the test bed project Swedish Hydrogen Development Centre and the Vinnväxt initiative Climate Smart Process Industry, are also run with support from, among others, Vinnova.

More research-oriented projects are also underway within the framework of, for example, FFI (Strategic Vehicle Research and Innovation Programme) focusing on, for example, hydrogen combustion engines and fuel cells for the propulsion of heavy traffic. Another example is GKN Aerospace and Chalmers' research on hydrogen-powered aircraft in the EU project ENABLEH2. In addition, more fundamental research projects are carried out without direct industrial participation in the development of next generation electrolysers, fuel cells and storage systems with the support of both the Swedish Energy Agency, the Swedish Research Council and SSF (Swedish Foundation for Strategic Research). One example is the initiative PUSH – Production, Use and Storage of Hydrogen.

Research and development often have an international character with cooperation within the framework of for example Horizon2020, IEA and Era-net. One example of the latter is the development of the Zero Emission Hydrogen Turbine Center (ZEHTC) at Siemens in Finspång.

In addition to developing new knowledge and technology, an important aim of all the projects run or joined by academia is to educate researchers in the field.

5.2. Competence supply in addition to research

In order to succeed in the realisation and subsequent operation and maintenance of these and future initiatives, Sweden needs to continue to invest in educating and ensuring relevant competence supply. Industrial actors and regions point for example to the shortage of installation engineers, operating and maintenance personnel for new technologies in the process industry, but also for the operation of fuel cell buses and other heavy traffic that may be converted to hydrogen operation. Here, collaboration and close dialogue between regions, industry and upper secondary and higher vocational schools have an important role to play. A good example of such collaboration is the work initiated in 2018 and run within the framework of the Western Swedish Chemistry and Material Cluster's "Competence supply" task area. The initiative has, for example, resulted in a broadening of higher vocational education towards the chemical industry to match their increased need for electrical and automation maintenance technicians, where the chemical industry supports training, for example in the form of work placement.

6. Financing opportunities for fossil-free hydrogen development in Sweden

The EU has announced that it will commit EUR 430 billion for hydrogen by 2030, of which EUR 180 billion in support and the remainder from the private sector. In the Green Deal's first call that closes on 26 January 2021, there is already money allocated for optimisation, upscaling and demonstration of large-scale electrolysers of 100 MWel for hydrogen production.[68] The European Commission has also mentioned that 37 percent of the funding in the forthcoming Horizon Europe Framework Programme will go to green initiatives. The various financial tools linked to the Green Deal are under development and one of the central tools is the EU Innovation Fund,[69] which opens up for both investment support and operational support for up to 10 years. The first application round is completed, but there will be recurring application opportunities until 2030 where Sweden and Swedish actors should be able to find good opportunities in development and financing for innovative technologies linked to renewable hydrogen.

Important Projects for Common European Interest (IPCEI)[70] is another tool within the EU that enables support from Member States to projects where the Member States is able to cover a higher share of project costs than normal in the application of state aid rules as well as supporting industrial uses. The industrial ecosystems that have been identified so far and may be relevant for joint projects are hydrogen, carbon neutral industry, raw materials and clean, connected and autonomous vehicles. To ensure Swedish participation in IPCEI projects, the Government proposes an investment of SEK 200 million in 2021, for 2022 an estimated SEK 200 million and thereafter SEK 70 million per year in 2023-2027. Companies participating in an IPCEI initiative will have the opportunity to avoid state aid rules if they work together with value chains from other EU countries. On the other hand, they may not automatically receive any allocated funds, but are able to apply for funds only if their own State allocates money.

There are also significant opportunities for public funding in the area from Swedish sources through, for example, the Swedish Energy Agency's Green Industry Leap and their call for the establishment of new so-called Competence Centres, the Swedish Environmental Protection Agency's Climate Leap and the government credit guarantees.

7. Safety aspects

Hydrogen has been handled on a large scale in Swedish industry for more than 100 years and consequently in this sector both procedures and safe working methods have been in existence for a long time. As regards the handling of hydrogen in other areas, the safety aspects of hydrogen are not always as established. Actors working on development of fossil-free hydrogen production are encountered by old myths about the risks of hydrogen, patchy knowledge among decision-makers and, not least, the lack of adapted legislation and standards, which complicate and increase the cost of market introduction. Overall, stakeholders from all sectors highlight the need to inform and educate decision-makers about the safety risks of hydrogen in relation to other fuels.

There are several actors who are knowledgeable on safety in hydrogen applications. RISE, Intertek and some industrial companies have test labs and there are many safety consultants with different specialisations in the area of safety available. An even more comprehensive approach is desirable from the actors who will now build complete systems in new environments for hydrogen storage and management.

The handling of hydrogen is subject to the ”Act on Inflammable and Explosive Goods” (LBE)[71] and associated ordinance. In addition to LBE, the Work Environment Act and a variety of other legislation also impose safety requirements in the handling of hydrogen. In addition, there are also standards, norms and directions for the execution, control, operation and maintenance of gas installations, but which are currently mainly intended for the energy gases LPG, natural gas, biogas, vehicle gas and liquefied methane.[72] The lack of directions adapted to hydrogen complicates permit processes. As already mentioned under 2.3., the need to adapt regulations, standards and directions for hydrogen is being raised both within the EU and at national level. Here in Sweden, the industry organisation the Swedish Gas Association is working on the issues. They are now developing directions for hydrogen filling stations, which will be published in the autumn of 2021, and are investigating risk and safety aspects in the event of future hydrogen input in the West Swedish transmission and distribution networks.

The industry organisation Hydrogen Sweden participates in a European partnership that maps laws, standards, norms and directions for hydrogen in various applications in society. The results are available in an open database that should be seen as an aid to the industry's actors and it is available under the name HyLAW Open database.

8. Sweden's comparative benefits and challenges

Table 3 presents a SWOT analysis for fossil-free hydrogen technology and new hydrogen value chains based on general properties and for Sweden in particular. The aim of this is to highlight Sweden's comparative advantages in comparison with the rest of Europe when it comes to industries and products linked to fossil-free hydrogen technology but also challenges and potential threats. The main features of the SWOT analysis with selected examples are also summarised below.

Strengths

One of Sweden's primary advantages in this case is the large proportion of fossil-free in the electricity mix in combination with a stable grid and an effective and efficient electricity market with relatively cheap electricity. Another advantage is the relatively high availability of surface area that enables the ambitious wind power expansion (land and offshore) required to meet the expected increased demand for fossil-free electricity and hydrogen. Overall, this gives the possibility of large-scale value added for Sweden's natural resources, where wind becomes electricity that becomes hydrogen that for example then together with iron ore becomes fossil-free iron and steel. In the fossil-free iron and steel example, there is the possibility of refining two of Sweden's natural resources at the same time, which is expected to result in increased export revenues and more jobs. Other examples of similar opportunities to add value and increase competitiveness are the value chains, the know-how and the climate-smart products that are now being developed from biomass and residual streams in combination with fossil-free electricity, such as Perstorp's "Project Air" or Liquid Winds methanol. Being an early adopter of fossil-free products is in itself a great strength to secure competitiveness and harvest export revenues.

Opportunities

Sweden's strong innovation environment and established partnerships between industry, academia and the institute sector are both a requirement and today a strength for successful transformation of industry and the transport sector as well as the development of new export goods and knowledge. Apart from the value chains and products mentioned above, Sweden has great opportunities to develop its export industry with products such as hydrogen-powered industrial turbines (Siemens Energy), heavy vehicles (Volvo Truck) and aircraft engines (GKN). Although there is no domestic production of complete electrolysers, there are good opportunities here to develop new building blocks in Swedish industry through the relatively many Swedish actors who are currently developing system components for electrolysers (Permascand), fuel cells (Sandvik Materials Technology, Höganäs, Impact Coatings) and complete fuel cell systems (Powercell). In addition to this, we have a number of small upcoming companies in systems know-how that can support hardware manufacturers and the development of integrated system solutions. The development of the new industrial fossil-free value chains at an early stage opens up the possibility of claiming the market and setting definitions for fossil-free value chains. The products are also expected to attract foreign expertise to Sweden, which in turn can strengthen Swedish industry.

In addition to reducing climate and environmental footprints and strengthening competitiveness, the various manufacturing technologies for fossil-free hydrogen, national fuel production, chemicals and mineral nitrogen will open up for increased resilience and reduced import dependence. This can in turn contribute to increased protection of civil society, food security and defence, etc. In this aspect, the decentralised hydrogen systems can add important values to existing infrastructure, for example in the form of electricity and gas pipelines and infrastructure for refuelling/charging mobility.

Weaknesses

Sweden also has a number of weaknesses in the area in relation to many other countries within the EU.

STRENGTHS

- Fossil free electricity mix, whereof a large share from renewable sources.
- Efficient and effective electricity market and relatively cheap electricity.
- Relatively stable electricity grid.
- Relatively large areas available, giving good potential for expansion of wind power.
- Relatively high proportion of biogas in the Swedish national gas grid (29 percent on 27 October 2020) – synergies and valuable complement as input raw material for the production of fossil-free hydrogen.
- Major point source emissions of biogenic carbon dioxide in pulp and paper industries and combined heat and power plants (total 31 million tonnes/year) – synergies with fossil-free hydrogen.
- Ambitious climate goals driving the transition of the process industry.
- Strong innovation environment and established partnerships between Swedish industry, academia and the institute sector
- Production of renewable fuels, driven by reduction obligation.
- Development of fossil-free steel (from iron ore mining to heat treatment and finished steel)
- Development of sustainable chemicals, such as methanol
- Development of hydrogen powered gas turbines.
- Development of hydrogen powered heavy vehicles and aircraft engines
- Development of system components for electrolysers and fuel cells and complete fuel cell systems

OPPORTUNITIES

- Cost-effective decarbonisation of several industries simultaneously through sector coupling in local/regional hydrogen clusters.
- Domestic production of new fuels, chemicals and products through hydrogen enables a good base for increased resilience and reduced import dependence.
- Great potential in fossil-free electrofuel/chemical production in pulp and paper industries, combined heat and power plants, alongside creating negative emissions via bio-CCS.
- Development of Swedish export industry: hydrogen-powered turbines, heavy vehicles and aircraft engines, system components for electrolysers and fuel cells, fuel cell systems, fossil-free hydrogen value chains for the production of, for example, fossil-free iron, steel and methanol.
- Foreign expertise is attracted to Sweden, which strengthens Swedish industry.
- Good opportunities for funding from the EU and the Swedish Government, including both CAPEX and OPEX for the establishment of pilot, demos and pre-commercial plants for hydrogen systems.
- Increased use of electricity for the production of electrolytic hydrogen opens up for significantly increased investments in wind power, which also creates jobs and exports.

WEAKNESSES

- Limited electricity capacity and power when installing large-scale electrolysis, in large cities in general, in electricity areas 3 and 4 in particular.
- Apart from a few local hydrogen networks and small and medium-sized hydrogen storage facilities, lack of hydrogen infrastructure.
- Lack of natural geological formations for hydrogen storage.
- Limited gas infrastructure (natural gas/biogas), which means: 1) few or no opportunities to switch disused pipeline networks into dedicated hydrogen networks. 2) limited possibilities to use biogas as input raw material for the production of fossil-free hydrogen, 3) limited possibilities for cost-effective storage and distribution over long distances for produced (electro) methane.
- No proactive infrastructure planning, transmission networks, gas networks
- Permit issues: complicated, lengthy and difficult to predict.
- Very limited experience of hydrogen production and use of hydrogen outside industry – uneven level of knowledge among decision makers for making well-informed decisions.
- There is no supporting regulatory framework for innovative and cross-sectoral business models.
- Relatively late "central government awakening" to the strategic importance of hydrogen in Sweden.

THREATS

- Permits for expansion of land and sea-based wind power in Sweden take too long and are unpredictable.
- Negative impact on the energy system (stability) if introduction is too rapid.
- Initially high investment costs – too highrisk for producers.
- The high cost of fossil-free hydrogen remains high or falls at a far slower rate than in forecasts.
- The driving force for the green transition is diminishing for example through continued low carbon dioxide price in the EU ETS, unfavourable revision of REDII for the production and use of renewable biofuels, electrofuels, fossil-free hydrogen for fuel cell vehicles, or taxonomy being designed so that parts of Swedish electricity production are not classified as sustainable.
- Limiting upscaling of electrolysis.
- Low technology maturity level for certain key processes, such as the introduction of green carbon in the HYBRIT process.
- Skills shortages (academics, operation and maintenance personnel etc).
- Tough competition for EU funding for development of hydrogen technology and infrastructure – Swedish industry lagging behind.

Table 3: Summary SWOT analysis with regard to fossil-free hydrogen technology and new hydrogen value chains, considered generally and for Sweden in particular.

Ambitious hydrogen development in Sweden requires ambitious expansion of fossil-free electricity production, primarily through the expansion of wind power, but also the expansion of new hydrogen infrastructure in the form of storage and local/regional gas grids. In this case, the relatively long and unpredictable permit processes are considered a major obstacle. Furthermore, Sweden has limited experience of gas overall in combination with a limited infrastructure for methane in the form of natural gas and biogas. In this respect, a limited methane infrastructure limits the potential for synergies such as producing fossil-free hydrogen from biogas in addition to electricity and water, and/or feeding, storing and cost-effectively distributing larger volumes of methane produced from fossil-free hydrogen and carbon dioxide. Sweden, in contrast to most of the rest of Europe, does not have any possibility to convert disused natural gas networks into pure hydrogen networks, which increases the cost of transition to the hydrogen economy.

Threats

The primary threats for the area are linked to the uncertainties surrounding the future availability of fossil-free electricity capacity, power and hydrogen at competitive prices, which in turn depend on permit processes, policy instruments, development and upscaling of electrolysis, etc. Although in the future there will be very good opportunities to seek support for R&D, investments and operating costs for fossil-free hydrogen technology and associated value chains, competition for EU funds is assessed to be tough. This in combination with the fact that in some parts of the area (concerning for example infrastructure and development of decentralised hydrogen systems) Sweden is considered to lag behind due to a relatively late “government awakening” to the strategic importance of fossil-free hydrogen for the country.

9. Action plan for actors and policy makers

The main focus of the strategy is that only fossil-free hydrogen should be rewarded. This does not thus imply a ban on for example blue or grey hydrogen, but that regulations and support systems primarily reward investments in fossil-free hydrogen.

The objective of the strategy is double, hydrogen is seen both as an important tool for achieving the climate goals and as a focus for new industrial initiatives and jobs. Therefore, the strategy's focus is on refining industry's products in several stages within the country's borders, in order to create innovations, jobs and export products rather than producing and exporting fossil-free hydrogen to other countries.

The five sections below present obstacles and proposed solutions in the form of policies to enable the desired development. Implementation of industry's initiatives and proposed policies can strongly contribute to Sweden's goal of climate neutrality by 2045, while also strengthening Swedish industry.

Chapter 3 "New value chains with hydrogen in Sweden" presents the initiatives of the various industries and value chains in the form of investments and decisions. Examples include:

- HYBRIT's investment in fossil-free steel with hydrogen as a reduction agent, and LKAB's major industrialisation of the same technology for fossil-free iron.
- Ovako is preparing the next demonstration step for steel heating using fossil-free hydrogen.
- Both Scania and Volvo AB invest in the development of hydrogen-powered trucks.
- Perstorp's "Project Air", where together with Fortum and Uniper, they are developing a unique process for sustainable methanol production by combining CCU and gasification.
- Preem and St1 are planning increased biofuel production using fossil-free hydrogen.
- St1, Liquid Wind and Jämtkraft are preparing for various investments in electrofuels.
- Nouryon plans to replace fossil hydrogen with fossil-free hydrogen for its hydrogen peroxide production.

1. The right conditions for the electricity system is a key issue for fossil-free hydrogen production

Limitations or future uncertainty as to available electricity capacity, output and hydrogen infrastructure are today identified as one of the largest barriers to electrification and fossil-free hydrogen development in the industrial and transport sectors.

One challenge when it comes to electricity production, grid expansion, electrification and fossil-free hydrogen development is the coordination between different authorities. The Swedish Energy Agency should have overall responsibility for coordinating these issues.

Today, the possibilities of increasing your power rating differ greatly depending on where you are in the country due to network constraints. Industries in Swedish electricity areas 1 and 2 do not currently see any major obstacles in this regard, while industries in electricity areas 3 and 4 already see such challenges. Furthermore, the price of electricity varies between the electricity areas, where the prices of electricity in areas 3 and 4 have been considerably higher than in 1 and 2. Thus, the conditions for access to the right electricity capacity vary greatly in different parts of the country, resulting in uneven competition when establishing both hydrogen investments and other industrial initiatives.

Electrolysers can be used for balance and regulation in the electricity grid. If a power distribution company would be helped by this, they can offer differentiated charges based on available power grid capacity. This may for example encourage an electrolyser to run at full capacity when the electricity price is low and the electricity grid price thus lower and, correspondingly, discontinue the electrolysis when the electricity grid is short of capacity and thus becomes more expensive.

With increased demand for fossil-free electricity from all industries that are now transitioning, together with the increased demand from hydrogen production, which in this strategy is estimated to approximately 45 TWh of hydrogen by 2045 corresponding about 55 TWh of electricity for the known projects that have chosen electrolysis as production tecnology , more fossil-free electricity production will be required.

Most forecasts show that wind power is the type of energy that achieves the lowest electricity production costs and electricity production from wind power in Sweden is expected to increase from 36 TWh in 2021 to 50 TWh in 2025, according to TSO Svenska Kraftnät's (Swedish transmission system operator) short-term market analysis. But after that development is more uncertain. The Swedish Energy Agency and the Swedish Environmental Protection Agency consider it "concerning that very few new licenses are being granted and many applications are rejected or reduced during the process". Therefore, a number of measures for better conditions and a long-term perspective for wind power production are proposed here.

Simplified and more predictable permit processes are required to produce the electricity when it is needed. The Swedish Government has taken a few steps in this direction, including a new committee of inquiry on modern and efficient environmental assessment and by proposing in the 2021 Budget Bill increased resources to the County Administrative Boards, the Swedish Environmental Protection Agency and the Swedish Energy Markets Inspectorate to shorten the processing times for permit applications.

In addition, an electrification commission has been appointed, which, together with the business sector and relevant actors, will urgently draw up an action plan for electrification of the busiest roads in Sweden and in other respects analyse other possibilities for electrification (including hydrogen).

Listed below are prioritised proposals for better conditions for the electricity system:

Policy 1.1: In 2021 the Government should instruct Svenska kraftnät (Swedish TSO) to develop an electricity grid plan that sets out which electricity lines are prioritised to enable industry to be electrified at a sufficiently high rate, and the timetable for laying the electricity lines.

Policy 1.2: In 2021 the Government should appoint a committee that is tasked with handling regulatory barriers that hamper attempts at new solutions based on new technologies or existing technologies used in new ways. In 2021, a decision should be made that at least three electrical lines can be included in regulatory sandboxes. This is in line with the proposals of the Committee for Technological Innovation and Ethics (Komet).

Policy 1.3: By 2022 at the latest, the Government should introduce requirements for Svenska Kraftnät (Swedish transmission system operator) to always evaluate alternatives to conventional grid investments, for example battery storage, when grid planning and making investment decisions.

Policy 1.4: At the latest by 2022 the Government should assign national interest status to transmission and distribution of electricity to be considered in relation to other interests such as defence and nature conservation in an overall assessment.

Policy 1.5: In 2021 the Government should clarify the Swedish Armed Forces' remit on facilitating coexistence with wind power, power grids and industries that transfom to reduce emissions, in that the Swedish Armed Forces, in its assessment of defense capability, should suggest how this can be solved, for example with an extra radar set to be paid for by the wind power developer.

Policy 1.6: In 2021 the Government should instruct the government agencies (Swedish Energy Agency, Svenska kraftnät (Swedish TSO), Swedish Agency for Marine and Water Management and the Swedish Environmental Protection Agency) to establish a national strategy for offshore wind power, corresponding to the strategies for onshore wind power and hydropower.

Policy 1.7: The Government should follow the European Commission's call and establish a Swedish target for offshore electricity production in an electricity system perspective, which should be decided by 2022.

2. New infrastructure required for hydrogen development throughout the country

Long-term policy rules are key for most investment decisions in both hydrogen and other areas. As a means to achieve a long-term approach, the Government should set up a planning goal for installed electrolysis power. The planning goal is not a nationally binding goal but an objective for government agencies to relate to and plan for. It is proposed that the goal builds on known planned projects (described in Chapter 3.6). Since development is rapid, a 50 percent adjustment is assumed for 2030 in the effect of the projects communicated when this strategy was launched in January 2021. For 2045 the capacity communicated is proposed, but this figure probably needs to be updated within a couple of years as more conclusions can be drawn from the tempo of hydrogen development.

As regards hydrogen infrastructure through grids in Sweden, this is currently limited to a few local grids in industrial areas (Stenugnssund cluster, Höganäs Industries in Höganäs, Sandvik Materials in Sandvik). Sweden establishing a nationwide hydrogen grid and eventually becoming part of a "European Hydrogen Backbone" is not considered a realistic scenario, as Sweden, unlike many European countries, lacks natural gas networks that can be converted to pure hydrogen networks. Instead, the Swedish natural gas grid on the west coast is planned to be converted in time into a dedicated biogas network with the aim of becoming the first network in Europe with 100 percent renewable gas. As described in Chapter 3, a probable ambitious hydrogen development in Sweden goes through local and regional hydrogen clusters where interconnection of nearby clusters may occur through the establishment of new hydrogen pipelines.

In addition to the infrastructure itself, there is also uncertainty in some industrial regions about the availability of fossil-free hydrogen at each location and associated logistics value chain. As mentioned in Chapter 3, several initiatives are already being taken in many sectors, but there is still a need to establish more cross-sectoral cooperation in the hydrogen area for example for industry, energy companies, technology suppliers, end users and government agencies and in collaboration between large and small companies.

Another obstacle is the law governing environmental permits, which is currently a barrier to the development of fossil-free hydrogen in Sweden. For example, if an industry wants to change the existing production of fossil hydrogen to the production of fossil-free hydrogen by electrolysis in a closed industrial area, the industry is now required to apply for a new environmental permit from the Land and Environment Courts. A desirable process here would be that it is possible to apply for an amending permit only for the addition of the electrolyser, something that the Inquiry on modern and effective environmental assessment (Environmental Assessment Inquiry, M 2020:06) is expected to investigate.

To contribute to an expanded hydrogen infrastructure, there are already a couple of political initiatives in the form of funding to be applied for from the Climate Leap and the fact that hydrogen will be included in the investment of SEK 500 million in 2021 and SEK 550 million in 2022 respectively, which the Government decided is to go to electrification of heavy vehicles.

Listed below are prioritised proposals for better hydrogen infrastructure:

Policy 2.1: The Government should set a planning goal at the latest by 2022 to have 3 GW installed electrolysis power by 2030 and at least 8 GW by 2045 to enable fossil-free development in many sectors.

Policy 2.2: During 2021 the Government should instruct the Energy Markets Inspectorate to create regulation with a revenue framework for hydrogen pipelines, which should be in place by 2023 at the latest. The expansion of hydrogen pipelines should be subject to concessions issued by the Energy Markets Inspectorate in the same way as electricity lines. The regulation should enable concession permits to be granted next to existing gas pipelines, as well as at electrical lines and road banks, for example. A first step is to enable "regulatory sandboxes" where step-by-step development of permit processes and regulations can be carried out in connection with the development of the first hydrogen pipelines.

Policy 2.3: Review the law governing environmental permits so that the industries and energy establishments that already produce and use hydrogen on a large scale and who want to convert to a more climate-adapted production of hydrogen in the same closed industrial area only need to submit a change notification instead of currently having to apply for a new environmental permit. This should be done in the framework of the Environmental Assessment Inquiry which will submit its report in December 2021.

3. Development of regulations and market conditions can increase the pace of fossil-free hydrogen

All sectors with interests in hydrogen development today state that there are no clear frameworks and market conditions for the development of production and use of fossil-free hydrogen on a large scale. The uncertainties apply, for example, to standards and definitions of what can be classified as renewable electricity and renewable hydrogen in the EU and Sweden, how the revision of the Renewable Energy Directive (REDII) for the production and use of renewable biofuels will fall out, how electrofuels and electrochemicals should be handled in relation to emission calculations and how the classification of and demand for hydrogen from colours other than renewable will be. The Commission is now investigating several of the issues as part of the design of the Green Deal, and its decisions will be presented at different times in 2021 (see Chapter 2.3.2).

There are also uncertainties related to current taxation rules and the role of hydrogen in the green gas principle. In addition, there is a need to develop advice and recommendations for hydrogen that can be used by rescue services and municipalities so that everyone has access to the same information and knowledge.

Listed below are prioritised proposals for better regulatory frameworks and market conditions:

Policy 3.1: Starting in 2020, the Government should review the taxation of hydrogen, electrofuels and electrochemicals, including production, distribution and various applications. The review should also include the risk of double taxation of hydrogen when used in electrical system applications. Ensure continued tax reduction for electricity consumed in electrolysis for the production of hydrogen. This should then be used in the revision of the Energy Taxation Directive, the state aid rules and the Renewable Energy Directive.

Policy 3.2: In 2021 the Government and agencies should ensure that policies and agencies interpret REDII in the same way so that electricity used as input in fuel production can be calculated on the basis of the national electricity mix.

Policy 3.3: At the latest in 2022 the Government should clarify the role of hydrogen in the green gas principle and the EU ETS.

Policy 3.4: During 2021 the Civil Contingencies Agency (MSB) should draw up national advice and recommendations for handling hydrogen and hydrogen pipelines to be used by all rescue services and municipalities.

Policy 3.5: At the latest by 2022 the Civil Contingencies Agency (MSB) should review its guidelines on reserve power and add to them the possibility of using renewable alternatives such as fuel cells.

4. Several fossil-free hydrogen initiatives in need of financing solutions

The EU is announcing EUR 430 billion by 2030 for hydrogen development. In order to create good conditions for Swedish hydrogen development that strengthens Swedish competitiveness, Sweden needs to actively work to share in the EU funds available to benefit the Swedish industrial transition and job creation. There is a need here for several agencies to coordinate not only the national grants and calls that are planned, but also how they can strengthen and coordinate grant processes and calls that are ongoing within the EU, such as the EU Innovation Fund.

The Swedish central government must also continue to invest in the development of hydrogen technology and hydrogen infrastructure, production and storage. The Green Industry Leap, the Climate Leap and credit guarantees can be used to share the risks between central government and industry.

A challenge for several climate projects is the unpredictability of the EU-ETS system, which creates a difficulty in calculating revenues. The Carbon Contract for Difference is a system that secures revenues from the sale of emission allowances. This means that the State hedges the difference between the current EU-ETS price and a "contract price" per tonne of carbon dioxide. If the ETS price exceeds the contract price, the State receives revenue instead, which can make the system less costly in the long run for the State. From the company's perspective, this helps to ensure the level of revenue, which helps to reduce the project's total cost of capital. The Contract for Difference has been tested in a couple of countries for electricity production, where the contract price has instead been about guaranteeing the electricity price. Often, a call is made by the State or an agency where projects may apply for the contract price they would need.

The Carbon Contract for Difference has been mentioned by the European Commission and is a possible policy instrument also in a Swedish context that can help, among other things, hydrogen projects to get started. This needs to be investigated more closely.

Listed below are prioritised proposals for more financing possibilities:

Policy 4.1: The Government should carry out a fast-track study concerning production support for fossil-free hydrogen projects during an introductory phase through the Carbon Contract for Difference, a system in which central government provides support based on the project's carbon reduction related to EU-ETS prices.

Policy 4.2: In 2021 the Government should instruct the Swedish Energy Agency to draw up a call for proposals for regions in Sweden as demo-show rooms to test and demonstrate cross-sectoral hydrogen systems. The aim is to establish a couple of Swedish hydrogen clusters ("Hydrogen Valleys").

Policy 4.3: In 2021 the Government should instruct Business Sweden to work with the entire hydrogen value chain to strengthen Sweden's position in the production of fossil-free hydrogen, hydrogen applications and the manufacture of hydrogen-related components.

Policy 4.4: The Government should promote measures to stimulate the market for fossil-free products, for example through guarantees of origin and traceability of fossil-free products and services.

5. Research, development and skills provision are key to long-term sustainability in several hydrogen value chains

There is a need to ensure knowledge about battery, hydrogen and fuel cell establishments among decision makers, the Civil Contingencies Agency, rescue services throughout the country and at the county administrative boards so that regional differences that may affect decisions do not arise or continue.

Actors in different sectors feel that there are preconceived opinions about hydrogen relative to other fuels as regards safety risks, and it is therefore deemed important to remove myths linked to the safety aspects of hydrogen.

During the autumn of 2020, the Swedish Energy Agency opened a call for proposals for new competence centres for sustainable energy systems that can enable new investments in hydrogen. The purpose of the call is to build up strong networks between academia and industry through long-term initiatives, enabling a direct and effective transfer of research findings.

Since the summer of 2020, the Foundation for Strategic Research, SSF, has supported a research centre in hydrogen research led by the Royal Institute of Technology, KTH, and includes seven research groups at four Swedish universities (Chalmers, KTH, Lund University, and Umeå University) and a research group at RISE. The "Production, Use and Storage of Hydrogen, PUSH" centre will run for five years and covers the entire value chain in a hydrogen-based energy system – production through electrolysis, storage and distribution and end-use in the form of electricity from fuel cells.

Listed below are prioritised proposals for more research, development and skills provision:

Policy 5.1: Work towards increased coordination between agencies regarding permit issues linked to the hydrogen area, for example by the Government appointing a coordinating agency.

Policy 5.2: The Government should ensure that universities and other higher education institutions continue to establish areas of research and innovation in the field of fossil-free hydrogen.

Policy 5.3: The Swedish Energy Agency should create competence nodes for training and education in hydrogen, the arrangement can be inspired by the node organisation of the Network for wind use.

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