Hydrogen strategy of Sweden: unpacking the multiple drivers and potential barriers to hydrogen development

Cetkovic, S.; Stockburger, J.; Quitzow, R.; Zabanova, Y.

Hydrogen Strategy of Sweden: Unpacking the Multiple Drivers and Potential Barriers to Hydrogen Development

Stefan Ćetković and Janek Stockburger

Abstract This chapter investigates the main elements, drivers, and challenges of the hydrogen sector in Sweden. A particular focus is placed on the approach of the Swedish government to hydrogen development and its internal and external dimensions. The domestic interest in hydrogen in Sweden has in the past been primarily focused on the decarbonization of hard-to-abate industrial sectors, in particular the steel industry. Given the current surplus of low-carbon electricity supply, which relies on hydropower, nuclear and increasingly wind power, the attention was solely directed towards domestic production and use of low-carbon hydrogen for the industry. With the growing importance of hydrogen at the EU level, accompanied by the introduction of an EU hydrogen strategy, investment funds and common standards, there has been a rapid increase in interest by business actors in various hydrogen sectors (e-fuels, green hydrogen, ammonia) in Sweden. Individual regions in Sweden have also taken the initiative and made use of EU funds to try position themselves in and benefit economically from the emerging hydrogen sectors. As most private investors aim to use green hydrogen produced by renewable energy sources, the demand for green electricity, particularly in onshore and offshore wind, is expected to skyrocket. The government, however, has so far failed to enact credible plans and policies detailing where and how new wind power projects will be built and which sectors may gain priority access to renewable electricity. There has also been a lack of effort in facilitating the realization of infrastructure for the potential transport of hydrogen through pipelines or Swedish ports. In light of the growing interest in low-carbon hydrogen, the considerable industry know-how and the vast renewable energy potential in Sweden, there is a pressing need for a more comprehensive approach by the government and a stronger alignment with the efforts of the EU and other Member States.

S. Ćetković (✉)
Institute of Political Science, Leiden University, Turfmarkt 99, 2511 DP The Hague, Netherlands
e-mail: s.cetkovic@fsw.leidenuniv.nl

J. Stockburger
Munich School of Politics and Public Policy, Technical University of Munich, Georgenstraße 99, 80798 Munich, Germany

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1 Introduction

Sweden has been a global leader when it comes to embracing low-carbon technologies and decarbonizing its economy. Over the past years, low-carbon hydrogen has seen a remarkable boost in interest by government and business actors in Sweden as a much-needed and promising technology on the path towards climate neutrality. Sweden is widely perceived as one of the most competitive countries for the development and utilization of low-carbon hydrogen, although fulfilling this potential is not without its challenges. There have been multiple domestic and external factors that have shaped the recent dynamic yet fluid development of hydrogen in Sweden. This paper provides an overview of the hydrogen sector in Sweden, focusing on the main domestic and external drivers and challenges. A particular focus is placed on the government approach to hydrogen development in Sweden and its relation to EU hydrogen policy.

This paper starts by presenting the domestic development of the hydrogen sector in Sweden and identifying the driving forces and possible barriers to the successful growth and system integration of hydrogen. This is done by looking at the interplay between public and private sector activities in a broader political-economic and material context. In the second part, the external dimension of the Swedish hydrogen strategy is discussed in more detail. The main focus is on how hydrogen development in Sweden, including both public and private sector, is related to the European policy and market context.

2 Domestic Hydrogen Development in Sweden

2.1 The Swedish Energy Mix and Sources of Emissions

Sweden has successfully established itself as a global leader in decarbonization efforts (IEA, 2019), while the country maintains one of the highest energy consumption rates per capita in the EU and internationally (TheGlobalEconomy.com, 2022). The electricity and heating sectors in Sweden have largely been decarbonized; the primary challenge remaining has been to curb emissions from industrial processes and transportation. In 2022, 41% of the electricity supply came from hydropower, 29% from nuclear, 19% from wind and 1% from solar power, while the remaining 9% was generated in combined heat and power plants and industrial processes (see Fig. 1). For heating, the residential and service sector rely dominantly on electricity and district heating, the latter being largely based on biomass (Swedish Energy Agency, 2022). The industry and transportation sectors are the key emitters, and together account for 64% of Swedish emissions. Road traffic is by far the dominant source of emissions in the transportation sector, with a share of 92%. In the industrial sector, the iron and steel industry is responsible for the highest amount of emissions (34%), followed by the minerals industry (19%) and refineries (18%)

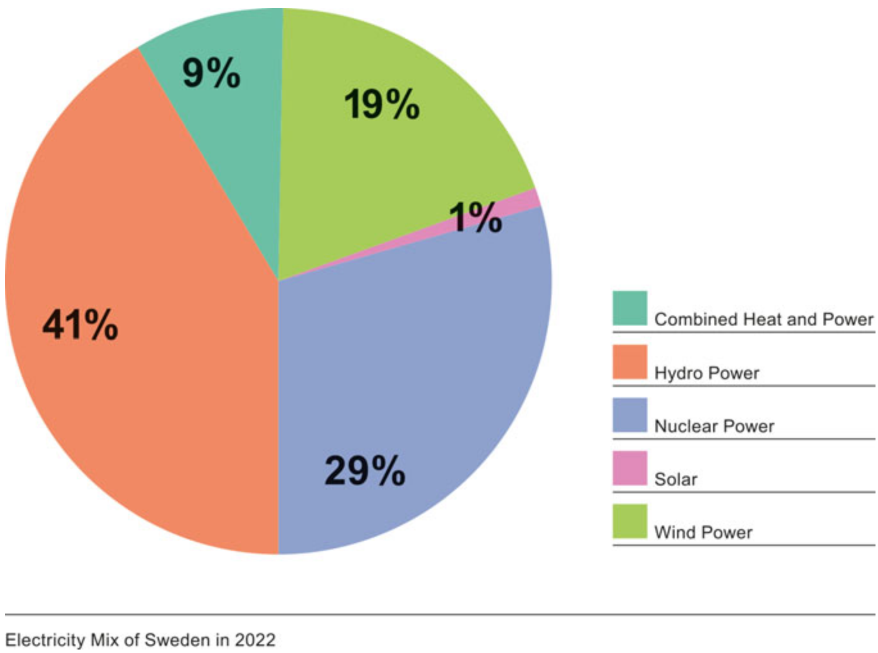

Fig. 1 Electricity production in Sweden in 2022. *Source* Based on the data from Statistics Sweden (2023), Electricity supply and use 2001–2022 (GWh). Retrieved November 13, 2023, from https://www.scb.se/en/finding-statistics/statistics-by-subject-area/energy/energy-supply-and-use/annual-energy-statistics-electricity-gas-and-district-heating/pong/tables-and-graphs/electricity-supply-and-use-20012022-gwh/

(Ministry of the Environment, 2020). It is against this background that the government has intensified efforts and activities to promote the utilization of fossil-free hydrogen in industrial processes and transportation in Sweden over recent years. This has been strongly influenced by the growing political interest and the accelerated market and technology developments in fossil-free hydrogen in the EU and around the world.

2.2 Developing a Swedish Hydrogen Strategy

In developing the country's hydrogen strategy, the government first tasked Fossil Free Sweden, an industry-based government initiative, with the formulation of a strategic plan for hydrogen development. In January 2021, Fossil Free Sweden published its hydrogen strategy (Fossil Free Sweden, 2021). The government then commissioned the Swedish Energy Agency to develop a comprehensive proposal for a national hydrogen strategy. The Swedish Energy Agency presented its draft of the hydrogen strategy in November 2021 (Swedish Energy Agency, 2021). Although the two published strategies differ somewhat in their scope, the outlined vision and priorities for hydrogen development are largely aligned. At the core of the interest in hydrogen is the decarbonization of the country's energy-intensive industries, particularly steel production, alongside long-haul transportation. The formulated targets for new electrolyzer capacities are very high compared to European targets. The document published by Fossil Free Sweden envisages the need for 3 GW in new electrolyzers by 2030, while the draft strategy of the Swedish Energy Agency proposed an even higher target of 5 GW, thus reflecting the growing industry interest. An additional 10 GW in electrolyzer capacity is to be put into operation between 2030 and 2045. According to an expert involved in the development of the national hydrogen strategy, while the EU hydrogen strategy served as an important background document, the specific Swedish targets for electrolyzer capacity were not based on EU targets. The national hydrogen strategic documents operate with the term ´fossil-free´ hydrogen, which leaves the possibility for using both renewable energy sources and nuclear power for producing hydrogen. The planned electrolyzer capacities are intended entirely to meet domestic demand. So far, there have been no articulated plans by the Swedish government and industry associations to import or export hydrogen. The main vision has instead been to export goods produced with fossil-free hydrogen, such as ´green steel´, and to enter the global supply chain for fossil-free hydrogen production technologies. Nevertheless, the draft of the national hydrogen strategy suggests that Sweden should assess whether or not to become a hydrogen exporter (Swedish Energy Agency, 2021, p. 9). Although an external hydrogen strategy has been lacking, the Swedish government and particularly Swedish industry stakeholders have increased their international engagement in this area.

As of October 2023, the official adoption of the national hydrogen strategy by the government is still pending. Sweden held general elections on 11 September 2022, which resulted in the formation of the first-ever minority center-right government supported by the far-right populist party Sweden Democrats. While it remains to be seen whether the new government will introduce substantial changes to the national hydrogen strategy, some preliminary assessments about the changing policy environment based on the first steps taken by the new government are included in this contribution.

2.3 The Swedish Government as a Driver of Hydrogen Development

The increasing interest in fossil-free hydrogen in Sweden is driven primarily by the government's goals of achieving climate neutrality by 2045 and reducing transport emissions (excluding aviation) by 70% until 2030, relative to 2010. These goals are formulated in the Climate Policy Framework, which was adopted by an overwhelming majority in the Swedish parliament in 2017 (Ministry of the Environment, 2021). Fossil-free hydrogen is seen as a key solution in the decarbonization of energy-intensive industries and in securing their competitiveness in the future global low-carbon economy. Hydrogen is also expected to contribute to the decarbonization of the transportation sector, especially for heavy vehicles and long-haul transportation including trucks, trains, ships, and airplanes. Furthermore, hydrogen is recognized as a potential means to help balance the electricity grid given the growing share of intermittent renewable electricity, particularly wind power.

Several government support measures have been in place that indirectly or directly encourage the production and utilization of fossil-free hydrogen. A key climate policy instrument in Sweden has been the carbon tax, introduced in 1991. Since then, carbon tax rates per emitted ton of CO2 have incrementally increased from €25 to €118 in 2022 (Ministry of Finance, 2022). Given that energy-intensive industries are already covered by the European Union Emission Trading Scheme, they are excluded from domestic carbon taxation. The carbon tax now primarily targets the transportation sector, with 95% of carbon tax revenues coming from motor fuels. Alongside the carbon tax, the government introduced the bonus-malus scheme in 2018, which provides favorable tax rates for low-emission vehicles, including both battery and fuel-cell vehicles. Thanks to government support, the purchase of low-emission vehicles in Sweden has surged in recent years, although this increase mainly pertains to rechargeable battery and hybrid vehicles. The deployment of fuel-cell vehicles, by contrast, has been negligible. By the end of 2021, 320,000 electrically powered vehicles were registered on Swedish roads, of which nearly 300,000 were passenger cars. In the same period, only 42 hydrogen-powered passenger vehicles and two lorries were registered (Trafikanalys, 2022).

The targeted government support for hydrogen production and infrastructure in Sweden has taken the form of two main support programs: Climate Leap and Industrial Leap. Climate Leap was introduced in 2015 and is administered by the Swedish Environmental Protection Agency. Its purpose is to provide financial support for low-carbon investments in the sectors not included in the EU Emission Trading Scheme. The funding is provided as a grant that covers a substantial share of the investment. The Swedish Environmental Protection Agency has noted a significant recent increase in interest in hydrogen projects under Climate Leap, which is attributed to the publication of the EU hydrogen strategy (Swedish Environmental Protection Agency, 2022, p. 40). In the period from 2015 to 2022 (March), 74 project applications relating to hydrogen were received, while 41 projects were awarded funding. In 2021 alone, 49 hydrogen-related project applications were submitted, with 29 receiving funding (Swedish Environmental Protection Agency, 2022). The typical hydrogen-related projects that have secured funding are refueling stations for hydrogen-powered vehicles, although production facilities for green hydrogen have also been supported. For example, in 2011 the company Strandmöllen AB received funding for its investment in 3 MW of electrolyzer capacity for the production of green hydrogen as transportation fuel (Strandmöllen, 2022). Industrial Leap, the second major support program, was launched in 2018 and is designed to support research, pilot, and demonstration projects for the decarbonization of industry. The program is administered by the Swedish Energy Agency and is expected to run through 2040 as

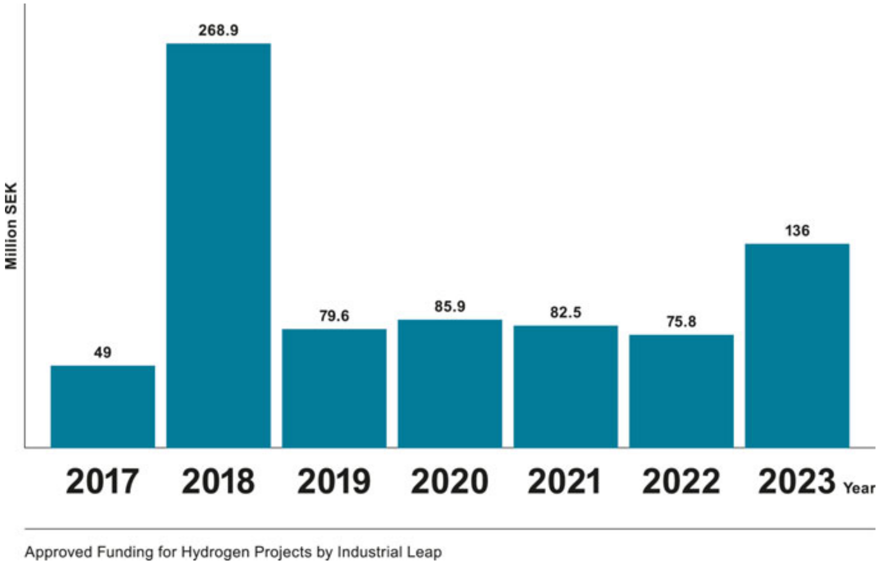

Fig. 2 Approved funding for hydrogen projects under industrial leap. *Source* Based on the data from the Swedish Energy Agency (2023). Beviljade projekt inom Industriklivet. Retrieved November 13, 2023, from https://www.energimyndigheten.se/forskning-och-innovation/forskning/industri/industriklivet/

part of the effort to facilitate the achievement of the climate-neutrality goal by 2045. In the period up to 2020, 73% of the entire program budget was allocated to decarbonization investments in the iron and steel industry, while the mining sector was the second largest beneficiary, accounting for 7.8% of the budget (Government Offices of Sweden, 2021). Both Climate Leap and Industrial Leap have been integrated into the Swedish National Recovery and Resilience Plan (NRRP) and will thus be funded by the Next Generation EU recovery instrument. Climate Leap has been granted the largest share of the Swedish NRPP budget (24.6%) with €810 million while €287 million (8.7%) has been allocated for Industrial Leap (Binder, 2022). Figures 2 and 3 display the total amount of government funding allocated to hydrogen projects through Industrial Leap and Climate Leap. The funding data for Climate Leap is inclusive of information up to July 2023, and for Industrial Leap up to October 2023.

2.4 Industrial Interests in Hydrogen Development

Enhanced industrial competitiveness is an integral part and the desired outcome of Sweden's ambitious decarbonization strategy through 2045. The export of fossil-free products and services that are produced in a fossil-free value chain is seen as a major opportunity for Swedish companies. Swedish industry has emphasized fossil-free

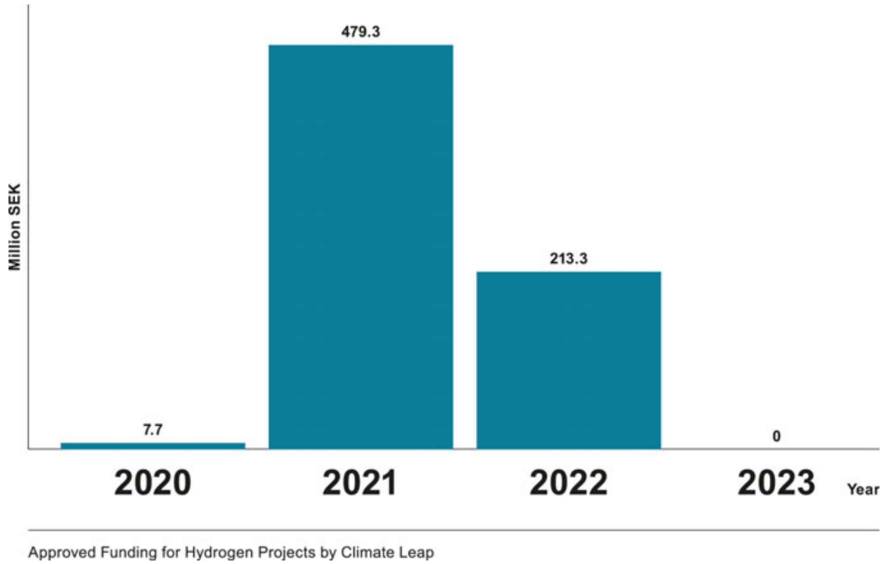

Fig. 3 Approved funding for hydrogen projects under climate leap. *Source* Based on the data from the Swedish Environmental Protection Agency (2023). Klimatklivets samlade resultat. Retrieved November 13, 2023, https://www.naturvardsverket.se/amnesomraden/klimatomstallningen/klimatklivet/resultat-for-klimatklivet/

hydrogen, with little attention paid to natural gas-based blue hydrogen. The strategy published by Fossil Free Sweden recommends that blue or gray hydrogen should not be banned, but instead that government regulation and support should focus primarily on fossil-free hydrogen (Fossil Free Sweden, 2021, p. 49). Several major industrial sectors, including steel production, the chemical industry and refineries, plan to switch their production, either completely or in large part, to fossil-free hydrogen or its derivates. In addition, the automotive industry in Sweden has been actively developing fuel-cell vehicles for both domestic and international markets. A growing number of Swedish companies are also considering entering the global hydrogen production supply chain as technology providers, subcontractors, or project developers. We will turn to these activities by external industries in later sections.

The iron and steel industry plays an important role in the Swedish economy. Sweden has rich and high-quality iron ore resources that are located mainly in the north of the country. Over 90% of the EU´s iron ore production originates from Sweden (SGU, 2020). Given the high emissions associated with the production of steel from iron ore, the transition to fossil-free hydrogen has been embraced as the main instrument for decarbonizing the Swedish steel industry. Hydrogen can be used as a substitute for fossil fuels at different stages of iron and steel production, including in the conversion of iron ore to iron sponge as well as in steelmaking from iron sponge or steel scrap. Several major projects for using fossil-free hydrogen in steel production have been initiated in Sweden. The most advanced project is

HYBRIT, a cooperation of the steelmaking company SSAB, the iron ore producer LKAB and the energy company Vattenfall. The goal of the project is to develop iron and steel production based on fossil-free hydrogen, which eventually is to become the main production method at SSAB's manufacturing units in Sweden and abroad. The HYBRIT project received support from the Swedish government through the Industrial Leap program and in 2022 was awarded funding from the EU Innovation Fund (Vattenfall, 2022a). A further large-scale fossil-free steel production project has been initiated by the newly founded company H2 Green Steel. The company, established in 2020, plans to build an entirely new iron and steel production facility in the city of Boden in northern Sweden, to be powered by an electrolyzer plant of 800 MW capacity (H2 Green Steel, 2022; S&P Global Commodity Insights, 2022). The announcement by H2 Green Steel of its plans for fossil-free steel production led the Swedish Energy Agency to increase the proposed national target for electrolyzer capacity to 5 GW by 2030, thus confirming the importance of industry plans for the government strategy. In September 2023, H2 Green Steel raised additional 1,5 billion euros in equity funds amounting to the total of 5,3 billion euros raised by the company but the final investment decision has not yet been taken (Parkes, 2023). Another Swedish steel manufacturer, Ovako, received the green light in November 2022 to construct an electrolyzer plant for producing fossil-free hydrogen which will be used to generate heat at its plant in Hofors. This project is supported by several companies including Volvo Group, Hitachi Energy, H_2 Green Steel and NEL Hydrogen (Steel Times International, 2022). The electrolyzer of 20 MW capacity was put into operation in September 2023. The excess hydrogen produced at this plant will be provided to Volvo for use in fossil-fuel trucks. According to the company officials, Ovako plans to roll-out the production and use of fossil-free hydrogen in all of its plants by 2030 under the condition that sufficient supply of fossil-free electricity is available (Martin, 2023).

The production of synthetic or electro fuels is another fossil-free hydrogen application that has attracted a growing interest in Sweden. Electro fuels are typically produced using fossil-free hydrogen and captured CO_2 of biogenic nature. Electro fuels can be used as feedstock in the industry, like eMethanol in the chemical industry, or in maritime transportation and aviation. Perstorp, one of the major Swedish chemical companies, has been part of Project Air, which aims to develop sustainable production of synthetic methanol using green hydrogen and carbon capture and utilization technology. Carbon will be captured from several sources, including the company´s operations as well as biomethane. The project, implemented together with the Finnish-owned energy companies Fortum and Uniper, received support from the Swedish Energy Agency and has most recently also been awarded funding from the EU Innovation Fund (Project Air, 2022). Sweden's largest refiner, Preem, located on the west coast of Sweden, has teamed up with Vattenfall to produce green hydrogen to decarbonize Preem´s operations and use it as an input for manufacturing synthetic fuels. The major offshore wind potential located on the Swedish west coast is to supply the majority of the renewable energy for producing green hydrogen (Vattenfall, 2022b). The Swedish company Liquid Wind, founded in 2017, has announced ambitious plans to scale up the manufacturing of eMethanol, which is to be used primarily as a transportation fuel in the maritime sector, for example (Liquid Wind, 2020).

The major automotive industry players in Sweden, Scania AB and Volvo AB, have been engaged in the development of hydrogen-based vehicles. While Scania AB has been particularly active in bringing fuel-cell trucks to market, Volvo AB has mainly focused on battery-based vehicles, although it has also been involved in testing the production of fuel-cell trucks for long-haul transport. Both companies are well-placed to become competitive manufacturers of fuel-cell vehicles in the global market. Hydrogen trucks, however, are still in the development stage, and many future challenges for mainstreaming light and heavy hydrogen vehicles remain. The representatives of Scania, for instance, have raised concerns regarding hydrogen-based heavy vehicles pertaining to issues of overall efficiency, maintenance costs and the availability of green hydrogen in Europe (Scania, 2021). In 2022, Scania officials announced a project to develop 20 fuel-cell trucks in cooperation with the US company Cummins Inc, but the company restated that fully battery powered trucks remain Scania's main strategy (Scania, 2022).

The hydrogen strategy of Fossil Free Sweden states that Sweden does not have competitive manufacturers of electrolyzers but has many companies that are increasingly taking part in the global hydrogen supply chain as technology providers and subcontractors (Fossil Free Sweden, 2021, p. 42).

2.5 Low-Carbon Electricity Mix and Different Bidding Zones

Sweden not only has an almost entirely carbon-free electricity supply system, it is also a net exporter of electricity. In 2021 it exported 25 TWh of electricity, mostly to neighboring countries including Finland, Denmark, Poland and Lithuania (Swedish Energy Agency, 2022). During the first half of 2022, Sweden became the largest electricity exporter in the EU (EnAppSys, 2022). The government, along with a growing number of industry players, see considerable potential in carbon-free electricity and a major comparative advantage for fossil-free hydrogen production. To this one should add a significant potential of untapped wind power Sweden, particularly with regard to offshore wind. The political and industry interest in offshore wind increased during the previous government, also driven by the growing need for renewable electricity in the production of green hydrogen in the future. As already noted, wind power has been identified by the Swedish industry as the preferable source for producing fossil-free hydrogen (RISE Research Institutes of Sweden, 2022). The previous government announced in 2022 the plans to ramping-up offshore wind deployment with the ultimate goal of achieving 120 TWh of electricity from offshore wind (Durakovic, 2022). To achieve this goal, the government proposed a more centralized approach to dedicate suitable areas for offshore wind and promote projects to interested investors. Previously, it was a sole responsibility of offshore wind investors to find a suitable location and apply for multiple permits. The transmission system operator was also tasked by the government with expanding the necessary grid capacity for connecting offshore wind parks. Offshore wind investors, based on the outlined policy, would be required to only bear the costs of connecting their projects to the grid connection points rather than investing in grid connection points themselves (Baltic Wind, 2022).

However, the new government in its coalition agreement pledged to revert that decision and prevent any government support for covering the connection costs for offshore wind projects (Moderata samlingspartiet et al., 2022). The new coalition agreement also does not define any concrete goals for the expansion of wind power. In its hydrogen strategy, Fossil Free Sweden called for the government to adopt an offshore wind strategy to provide long-term certainty for the planned hydrogen projects (Fossil Free Sweden, 2021). Despite the significant potential, Sweden has so far built only 192 MW of offshore wind, while as much as 15 GW of projects are in the pipeline and could become operational before 2030 (Baltic Wind, 2022). See Figs. 4 and 5 for an overview of the deployment of onshore and offshore wind power in Sweden. Torn between the demands to increase the supply of low-carbon electricity by tapping into the vast offshore wind power potential, on the one hand, and the local opposition and negative stance of the Sweden Democrats towards wind power, the current government commissioned a new study for assessing the potential for improving the development of offshore wind projects expected to be published in July 2024. This may risk further delays in the development of offshore wind projects (Baltic Wind, 2023). In the meantime, the government decided in May 2023 to authorize the construction of two offshore wind parks off the West coast despite the vocal opposition of the Sweden Democrats and local policymakers (Szumski, 2023).

In contrast to the somewhat ambiguous position on wind power, the new government has been unified in its support for maintaining and expanding nuclear power. The Framework Agreement on energy policy, adopted in 2016 by all parliamentary parties except for the far-right Sweden Democrats, set the target of achieving a 100% renewables-based electricity system by 2040. Importantly, however, the document does not envisage a ban on new nuclear power plants, nor does it allow for closing the existing nuclear power plants based on political decisions (Swedish Nuclear Society & Analysgruppen, 2016). The status of nuclear power has been a contested issue in Swedish politics. The more left-leaning parties have insisted on transitioning towards renewable energy sources, while the conservative and right-leaning parties have remained supportive of nuclear power. After the right-leaning parties won a slim majority following general elections in September 2022, they promised to facilitate a fast expansion of nuclear power capacities in Sweden through favorable administrative and financial conditions (Moderata samlingspartiet et al., 2022). In the coalition agreement, the newly elected government also replaced the goal of 100% renewable to 100% fossil-free electricity by 2040, clearly implying the important place of nuclear power in the future electricity mix. The implications of the war in Ukraine on energy supply chains and the necessity to make the domestic electricity supply more reliable have been used as arguments by the government for the accelerated deployment of nuclear power. In September 2023, the government tabled a new legislative

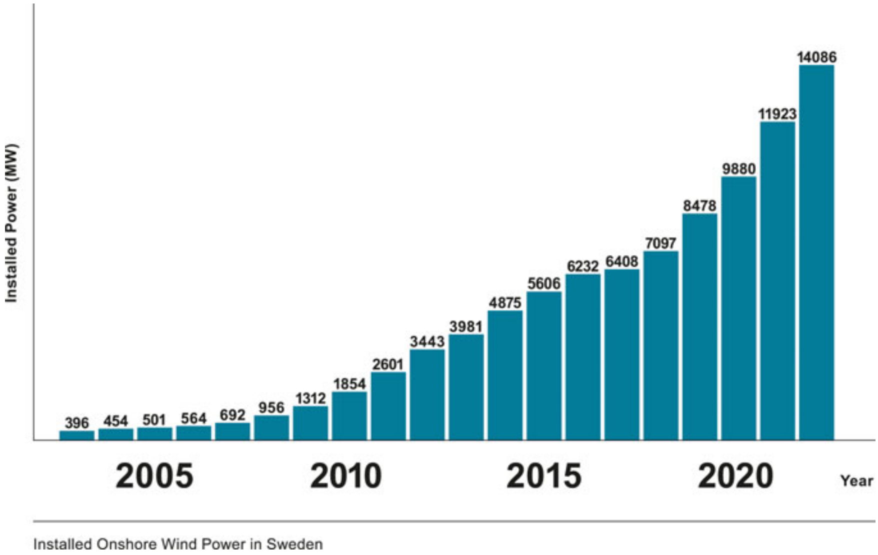

Fig. 4 Cumulative installed capacity of onshore wind in Sweden. *Source* Swedish Energy Agency (2023). Number of Wind Turbines, Installed Capacity and Wind Power Production by Installation Type, Whole Country, 2003-, Retrieved November 13, 2023. https://pxexternal.energimyndigheten.se/pxweb/en/Vindkraftsstatistik/Vindkraftsstatistik/EN0105_5.px/

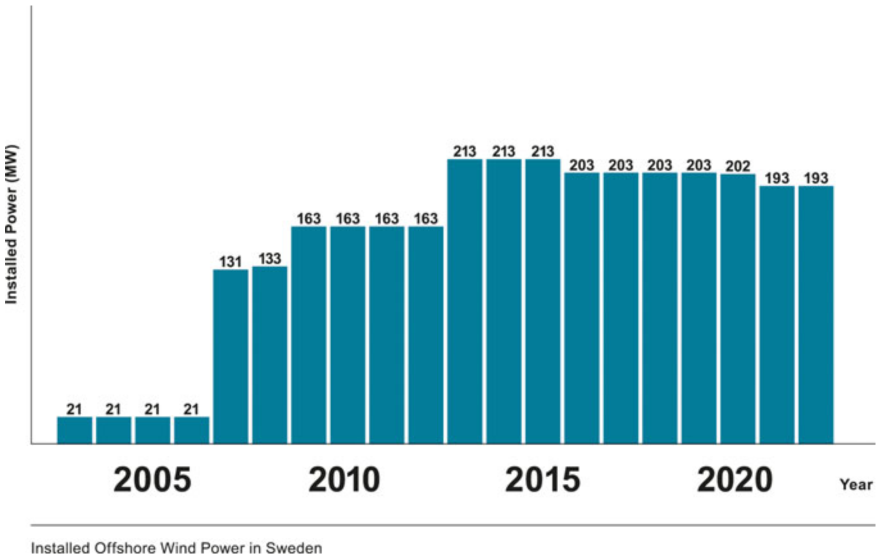

Fig. 5 Cumulative installed capacity of offshore wind in Sweden. *Source* Swedish Energy Agency (2023). Number of Wind Turbines, Installed Capacity and Wind Power Production by Installation Type, Whole Country, 2003-, Retrieved November 13, 2023. https://pxexternal.energimyndigheten.se/pxweb/en/Vindkraftsstatistik/Vindkraftsstatistik/EN0105_5.px/

proposal which lifts all restrictions to the construction of new power plants in Sweden (Government Offices of Sweden, 2023).

An important feature of the Swedish electricity market, which strongly affects fossil-free hydrogen investment decisions, is the separation into four bidding zones for electricity, as established in 2011. The reasoning behind the four different price zones is to encourage the construction of production capacities in areas affected by electricity shortages (Hansson et al., 2017). In the northern parts of the country (bidding zones SE1 and SE2), electricity has been historically cheaper due to surplus electricity production from hydropower and increasingly wind power, combined with lower levels of electricity consumption (Hansson et al., 2017). In the southern part of Sweden (bidding zone SE3), electricity production comes mostly from nuclear power, which in combination with higher levels of consumption leads to higher electricity prices. The existence of four different bidding zones with different electricity generation structures has implications for hydrogen investments and will lead to regionally specific hydrogen development trajectories. This will further be influenced by the EU additionality criteria and the necessity for hydrogen production facilities to meet spatial correlation requirements by purchasing renewable electricity from the same bidding zone. The major green steel projects are located in the northern part of the country, due to the appeal of cheaper and renewables-based electricity. H2 Green Steel, for instance, signed a long-term Power Purchasing Agreement with Statkraft for 2 TWh of annual hydropower-based electricity for its green steel project in Boden (Statkraft, 2022). Northern Sweden also offers large available areas that can be used for the generation of renewable energy from wind power (Fossil Free Sweden industry strategy, 2021). The company Svevind plans to build a large onshore wind power park with a total capacity of up to 4 GW in northern Sweden (Svevind, 2021). The production projects of renewable hydrogen and its derivatives in bidding zones SE3 and SE4 will need to rely primarily on onshore and offshore wind power which will need to be significantly expanded.

2.6 Lack of Gas Infrastructure and Natural Storage for Hydrogen

Sweden initiated an early transition to biomass and waste-based heating, which resulted in an underdeveloped natural gas infrastructure. Natural gas plays a minor role in the Swedish energy mix, accounting for less than 2% of total energy consumption in 2020 (Swedish Energy Agency, 2022). The absence of a well-developed gas infrastructure in Sweden limits the possibility to store and transport hydrogen. The Swedish Energy Agency, in its hydrogen strategy draft, indicates the possibility of transporting hydrogen via train, truck or ship in cases where no pipelines exist (Swedish Energy Agency, 2021). However, the Swedish industry estimates that the absence of gas infrastructure will reduce the possibilities of cost-effective transport of hydrogen over long distances (Fossil Free Sweden, 2021). Additionally, Sweden lacks hydrogen storage opportunities because geographically the country has only few salt caverns that can be used for future hydrogen storage. One interviewee said that Sweden could benefit from a broad connection to the EU gas infrastructure, as the country's storage possibilities would be expanded. A plan exists for Sweden to become a part of the so-called "European Hydrogen Backbone" over the coming decades (EHB, 2022). The Hydrogen Backbone is an initiative by 33 infrastructure operators with the goal, among other things, of accelerating decarbonization and connecting regions "with abundant supply potential with centers of demand" (EHB, 2022, p. 4). In 2022, gas infrastructure operators from Finland and Sweden, Gasgrid Finland and Nordion Energi, launched the Nordic Hydrogen Route initiative to build a cross-border infrastructure for transporting hydrogen through pipelines in the Bothnian Bay (Nordic Hydrogen Route, 2022). The Nordic Hydrogen Route is designed as part of the European Hydrogen Backbone Initiative, based on the idea to link the hydrogen sectors in Sweden and Finland with the rest of Europe. However, the Swedish industry assessment is that, because the country simply lacks the necessary infrastructure, it is "not a realistic scenario" for Sweden to become part of the European Hydrogen Backbone (Fossil Free Sweden, 2021, p. 8).

2.7 Summary of Opportunities and Trade-Offs

Ambitious climate goals, a highly competitive and future-oriented industry and available emission-free electricity constitute the main opportunities for Sweden to build a successful hydrogen sector. Sweden possesses both a high emerging domestic demand and attractive domestic supply conditions for fossil-free hydrogen. So far, the Swedish government has not taken a particularly proactive role when it comes to making long-term strategic decisions for spurring the domestic hydrogen market. While a bottom-up, industry-driven approach proved fruitful in the early experimentation phase, the mainstreaming of fossil-free hydrogen may require more active government planning. This concerns in particular the question of securing a sufficient supply of low-carbon electricity and the related grid capacities in the future. Given the plans for massive electrification of the Swedish economy, electricity demand is set to rise significantly. The scenarios calculated by the Swedish electricity grid operator project that electricity demand will almost double by 2050 from the current 140–266 TWh, under the scenario in which the electricity mix is based on a combination of nuclear and renewable energy (Svenska Kraftnät, 2021). The study notes that the future electricity demand may turn out to be even higher. The coalition agreement of the new government foresees that the electricity demand will already increase to at least 300 TWh by 2045 (Moderata samlingspartiet et al., 2022). Both the electricity price and renewable energy share will be central to building a domestic green hydrogen industry that is capable of entering the global supply chains and foreign markets. The question of whether Swedish companies will be in a position to export hydrogen and its derivatives also remains to be addressed. In the absence of a government vision for the future electricity mix and support for renewable energy infrastructure, important conflicts, and bottlenecks in the supply of low-carbon electricity may emerge. Given the lack of a suitable gas infrastructure, the issues of whether and how hydrogen will be transported within and outside Sweden, and under what conditions hydrogen gas infrastructure can be built, have also remained largely unresolved (RISE Research Institutes of Sweden, 2022).

3 External Dimension of Hydrogen Development in Sweden

So far, Sweden has lacked a coherent external hydrogen strategy, due to the fact that hydrogen development has largely evolved in a bottom-up fashion, driven by private sector decisions and market impulses. This is not to say that the hydrogen sector in Sweden will not gradually become more embedded into regional and international supply chains, on the contrary. Sweden as an open market economy and an EU Member State is deeply integrated into the Nordic and European markets and policy frameworks. In that sense, the future of the hydrogen sector in Sweden is closely intertwined with the regulatory market and infrastructural developments in the Nordic region and the EU. Many companies active in the growing hydrogen market in Sweden have already established partnerships and launched joint projects with business partners from abroad in a bid to strengthen their business case in a promising but uncertain investment environment.

3.1 Strategic Objectives of the External Hydrogen Dimension in Sweden

Given the ambitious plans for industrial advances through the utilization of fossil-free hydrogen in Sweden, the priority for Swedish industry and government has increasingly been to achieve favorable regulatory conditions for the emerging hydrogen industry. The industry and the government have turned their attention in particular to the evolving EU hydrogen standards to ensure that the regulatory framework is not an obstacle to ongoing and planned investments in fossil-free hydrogen. On the industry side, the objective has also been to explore new partnerships for projects in hydrogen production, infrastructure, and transport. This is mainly occurring within the Nordic regional cooperation, while new avenues for international cooperation and trade in hydrogen and its derivatives are also being explored. The Swedish government has been less active in steering and supporting the internationalization of the domestic hydrogen sector.

3.2 Lobbying for Favorable EU Hydrogen Standards

The draft of the national hydrogen strategy states that Sweden intends to take an active role in the dialogue in European and international fora regarding technical, economic and regulatory standards on hydrogen (Swedish Energy Agency, 2021, pp. 8–9). Public and private sector efforts have been particularly focused on negotiations over the new EU hydrogen rules. The most contested provision has been the ´additionality criteria´, which is meant to ensure that electricity deployed to produce green hydrogen is generated through additional renewable energy installations and not from existing capacities. The Swedish industry has been vocal in making the case that such a rule should not apply to countries like Sweden that already have a high share of renewable energy and an oversupply of electricity. The stringent additionality criteria seem particularly challenging for the decarbonization of the steel industry, which requires a substantial electricity supply for generating fossil-free hydrogen. Swedish industry actors have thus proposed that the additionality criteria should not apply to countries that have a higher than 50% share of renewable energy in their electricity mix (Swedenergy, 2021). Such a position has also been officially backed by the Swedish government, which has opposed any requirements that fossil-free hydrogen production facilities be directly connected to newly constructed renewable electricity plants (Ministry of Infrastructure, 2021). Swedish industry associations have further opposed any mandatory renewable energy targets for the industry in the new Renewable Energy Directive, as such targets would discriminate against the use of fossil-free electricity that may be generated by nuclear power plants (Swedenergy, 2021). The final adopted rules in the hydrogen delegated act which relaxes the additionality requirement for bidding zones where renewable electricity share exceeds 90% or is below the defined threshold of CO_2 intensity largely address the concerns of the Swedish industry.

3.3 External Actions of the Swedish Industry

The Swedish industrial players have increasingly been exploring opportunities to transfer their acquired expertise in green hydrogen production to external markets and develop commercial applications for hydrogen and its derivatives. There is, for instance, an emerging cooperation between Swedish and Spanish companies, as both countries share highly ambitious green hydrogen strategies. In 2021, H2 Green Steel signed an agreement with the major Spanish energy company Iberdrola to build an electrolyzer plant in Spain for green steel production (Iberdrola, 2021). In the opposite direction, the Spanish fertilizer producer Grupo Fertiberia, reached an agreement in 2021with the authorities of the northern Swedish region of Norrbotten to construct a green ammonia and fertilizer plant featuring a 600 MW electrolyzer. The plant could become operational by 2026 and is also expected to export green ammonia abroad (Ammonia Energy Association, 2021).

In collaboration between industrial actors, regional government authorities and scientific institutes, hydrogen development in Sweden has increasingly taken the form of clusters centered around regional ports. Each regional cluster seeks to attract hydrogen investments and benefit economically from the emerging fossil-free hydrogen sector. Some of the clusters have been actively supported by the EU Hydrogen Valleys program, which is part of the EU Smart Specialization Platform (European Commission, 2022). The previously mentioned northern region of Norrbotten, which is host to the two major green steel projects, is one of the main hydrogen clusters. In the port city of Lulea, Uniper and ABB have launched the Bothnian Bay H2 initiative, which will enhance the development of an additional hydrogen hub (Uniper, 2021). The plans provide for construction of green hydrogen production capacities based on wind power. Green hydrogen is meant for industrial processes or as an input for producing maritime fuels. The export of hydrogen derivatives is also planned. The central-eastern region of Gävleborg has also invested in efforts to establish another hydrogen cluster, the so-called Mid Sweden Hydrogen Valley, supported by the EU Hydrogen Valleys program. The remaining two regional clusters are located in the south, around the port city of Trelleborg, and in the central-western region with a focal point in Göteborg (Region Gävleborg, 2022).

The import of hydrogen has not been high on the agenda, given the good domestic conditions for fossil-free hydrogen production and limited gas infrastructure for transporting hydrogen. However, under the previously mentioned Nordic Hydrogen Route, plans for constructing a hydrogen pipeline infrastructure have been announced. Such an infrastructure may create entirely new possibilities in the internationalization of the Swedish hydrogen sector, although its realization remains highly uncertain.

4 Conclusion

Sweden has witnessed a very dynamic and diverse development of the fossil-free hydrogen sector in recent years. With its ambitious decarbonization targets and various support programs for low-carbon technologies, the Swedish government has put in place an overall support framework while leaving it to the private sector to make technology and investment choices on the path to decarbonization. With the current surplus supply of carbon-free electricity, the utilization of fossil-free hydrogen has advanced domestically as a logical choice for cutting emissions in strategic energy-intensive industries such as iron and steel. The actions of Swedish stakeholders towards the utilization of fossil-free hydrogen in steel production have preceded the EU hydrogen strategy and policy framework. In many other sectors, including hydrogen-based transportation and synthetic fuels, the interest of industry and regional governments has largely been fueled by the growing support for fossil-free hydrogen at EU level. The development of a charging infrastructure for hydrogen vehicles, industrial hydrogen pilot projects as well as the establishment of regional hydrogen clusters in Sweden have all been decisively supported through EU funds.

Both of the main government support programs, Industrial Leap and Climate Leap, have been incorporated into the EU Next Generation Fund. The emerging EU hydrogen rules and standards will also have vast implications for the Swedish fossil-free hydrogen sector. At the same time, the draft of Sweden's national hydrogen strategy is only loosely linked to the EU hydrogen strategy.

The Swedish government has so far avoided embracing a stronger steering role in hydrogen development. On the one hand this has to do with the traditional preference by the Swedish government for a market-based approach, while on the other hand it is due to the inherited liberalized and regionally integrated electricity market, which makes it more difficult for the government to assume a steering role. The previous government coalition launched efforts to develop a national hydrogen strategy and accelerate the implementation of offshore wind projects. The newly elected government, however, has signaled less enthusiasm for wind power, instead placing the main emphasis on maintaining and expanding nuclear power. In the absence of clear and decisive governmental steering, the development paths of the fossil-free hydrogen sector in Sweden will remain fluid and largely driven by industry initiatives. Most importantly, without an organized and timely utilization of the Swedish renewable energy potential, mainly in wind power, the investments in fossil-free hydrogen will likely be at risk. This in turn indicates that the EU´s influence will continue to be of exceptional importance and that the EU may require a more holistic approach to fossil-free hydrogen which would include a more coordinated policy strategy along the entire hydrogen production and use cycle.

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Stefan Ćetković is an assistant professor of energy and environmental politics and policy at Leiden University in the Netherlands. Previously, he was a senior researcher and lecturer at the Munich School of Politics and Public Policy at the Technical University of Munich, Germany. He has a long experience as a researcher, lecturer and policy advisor on energy and climate issues at the intersection between politics and technology.

Janek Stockburger is a graduate student at the TUM School of Governance in Munich. He is currently enrolled in the master's program "Politics and Technology" (M.Sc.). Previously, Janek completed his Bachelor of Science in electrical engineering and information technology at the Karlsruhe Institute of Technology (KIT). In his master's degree, Janek specialized in environmental and climate policy. Janek's focus includes energy policy, industrial policy, and the geopolitics of energy transition.