Will the Nordics Become an Export Hub for Electro Fuels and Electricity?

Citation for the original published paper (version of record):
Karlsson, K., Radoszynski, A., Münster, M. et al (2024). Will the Nordics Become an Export Hub for Electro Fuels and Electricity?. Lecture Notes in Energy, 101: 167-193.
http://dx.doi.org/10.1007/978-3-031-58897-6_8

Will the Nordics Become an Export Hub for Electro Fuels and Electricity?

Kenneth Karlsson, Andrea Marin Radoszynski, Marie Münster, Lissy Langer, Ioannis Kountouris, Johannes Felipe Giehl, Jenny Westerberg, Sidsel A. Nissen, Alexander Daabech, Mathias Bache, Lars Hedemann, Julia Kirch Kirkegaard, and Julia Hansson

Abstract The Nordics have a huge renewable energy potential, mainly in the form of onshore and offshore wind as well as biomass potentials and can deliver some of the lowest electricity prices in Europe. They could export large amounts of electricity and hydrogen, supplying mainland Europe and abroad. But where and when should wind, PV and green fuel production capacity be built, and what kind of infrastructure is needed? Within the Nordics—who can/will become a net exporter of electricity and green fuels?

K. Karlsson (✉) · A. M. Radoszynski
Energy Modelling Lab, Copenhagen, Denmark
e-mail: kenneth.karlsson@energymodellinglab.com; Andrea@energymodellinglab.com

M. Münster · L. Langer · I. Kountouris
DTU Management, Kgs. Lyngby, Denmark
e-mail: maem@dtu.dk; lilang@dtu.dk; iokoun@dtu.dk

J. F. Giehl
Copenhagen Business School, Copenhagen, Denmark
e-mail: jfg.eco@cbs.dk

J. Westerberg
Profu, Stockholm, Sweden
e-mail: jenny.westerberg@profu.se

S. A. Nissen · A. Daabech · M. Bache · L. Hedemann
Brinckmann, Århus, Denmark
e-mail: san@brinckmanngroup.com; ada@brinckmanngroup.com; mba@brinckmanngroup.com; lhe@brinckmanngroup.com

J. K. Kirkegaard
DTU Wind, Roskilde, Denmark
e-mail: jukk@dtu.dk

J. Hansson
IVL Swedish Environmental Research Institute, Chalmers University of Technology, Göteborg, Sweden
e-mail: Julia.hansson@ivl.se

M. Labriet et al. (eds.), *Aligning the Energy Transition with the Sustainable Development Goals*, Lecture Notes in Energy 101,
https://doi.org/10.1007/978-3-031-58897-6_8

To avoid sub-optimal solutions, some overall analysis and planning may be needed to secure societal benefits and reduce the overall cost. By comparing plans and visions for the build-out of electrolyser capacity, electricity and gas infrastructure, and wind and solar projects, we discuss consistency (or lack thereof) in the project pipelines. Furthermore, the future role of the Nordics is discussed by comparing scenario analysis from different modelling teams to identify robust conclusions and critical uncertainties.

The impact goes beyond SDG 13 (Climate action) and supports e.g., SDG 8 (Decent work and economic growth) by implementing a more sustainable economic system and also offers the opportunity to provide affordable and clean energy (SDG 7).

Key Messages

- The Nordics are in a position to become a major exporter of hydrogen and electricity—this conclusion is robust under the analysed situations.
- Methodology significantly influences hydrogen demand modelling conclusions. Back-casting tends to overestimate in the short and medium term, while demand-side optimization may underestimate.
- The implementation of hydrogen and electro fuels has direct positive impacts on several sustainable development goals (SDGs 7 on energy, 9 on industry, 11 on cities, and 13 on climate) but also indirect positive effects (on SDGs 8 on work and economic growth, and 12 on efficient use of resources).
- Renewable energy projects in the Nordic countries face local resistance, potentially causing delays in Power-to-X (PtX) development. Public concerns, including safety issues and the fair distribution of costs and benefits, are anticipated.

1 Introduction

The Nordics have a huge renewable energy potential, mainly in the form of hydropower, onshore and offshore wind, and can deliver some of the lowest electricity prices in Europe (Sovacool 2017) They could export large amounts of electricity, hydrogen, and green fuels, supplying Europe and abroad (Ikäheimo et al. 2018) However, studies show that aspects like the regional availability and diversity of renewable energy sources (Gea-Bermúdez et al. 2023; Ikäheimo et al. 2018; Karlsson and Meibom 2008) or infrastructure for imports and exports (Pedersen et al. 2022) influence the feasibility and demand for hydrogen and green fuels. With the expected limited global supply of sustainable biomass (Haberl et al. 2010), e-fuels based on hydrogen derived from electrolysis may play an important role (Mortensen et al. 2020), particularly for the chemical industry, and heavy long-haul transport such as aviation and shipping. But where and when should wind, PV, and electrolyser capacity be built, and what kind of infrastructure is needed? Can the Nordics compete with countries in the South that have abundant solar potentials?

Within the Nordics—who can/will become a net exporter of electricity and green fuels? Here, green fuels are defined as fuels based on carbon neutral electricity or sustainable biomass.

In a race to decarbonize and fulfil the net zero target, EU members adopted national Power-to-X strategies and targets as green hydrogen was seen as the renewable energy carrier that could decarbonize hard-to-abate industries. As of writing this, nineteen EU countries have adopted a national hydrogen strategy, one has implemented a roadmap, and Italy has produced preliminary guidelines. Among the Nordic countries, Denmark is the most ambitious, targeting between 4 and 6 GW of electrolyser capacity by 2030 according to Danish Ministry of Climate, Energy and Utilities (Klima-, Energi- og Forsyningsministeriet 2021) The Danish Energy Agency (DEA) has also set up a "Power-to-X taskforce" to ensure alignment with related resource and consumption sectors and to nurture the development of a market. Sweden follows Denmark in terms of ambitions, targeting 5 GW according to the Swedish Energy Agency (Energimyndigheten 2022), while Norway does not specify a target in its national strategy. Germany, in turn, boasts a 10 GW electrolyser capacity target, also reflecting the country's larger size according to the Federal Government of Germany (Bundesregierung 2023). The plans and ambitions on the role of green hydrogen and e-fuels presented in the early 2020s were reignited by the decision to end dependency on Russian natural gas in early 2022. For countries to achieve these ambitious targets, however, two overall prerequisites must be met (1) enough renewable electricity, and (2) a willingness-to-change.

To avoid sub-optimal solutions, some overall analysis and planning may be needed to secure societal benefits and reduce the overall cost. The future role of the Nordics is discussed by comparing scenario analysis from different modelling teams to identify robust conclusions and critical uncertainties.

Combating climate change through renewable energies provides extensive, sustainable economic potential. Climate protection measures offer the potential to improve global development prospects and contribute to the Sustainable Development Goals of the United Nations.

The impact goes beyond SDG 13 "Climate action" and supports e.g., SDG 8 "Decent work and economic growth" by implementing a more sustainable economic system. It also offers the opportunity to provide "affordable and clean energy" (SDG 7).

2 Who Will Be the Future Net Exporter of Power and Green Fuels?

2.1 Hydrogen in the Context of the Nordics

The Nordics offer great potential for the integration of hydrogen into the overall energy system. The European Union sees hydrogen as a key element of its strategy to reduce greenhouse gas emissions, and the Nordics are often identified as role models for the energy transition. Their high potential of renewable energy sources offers the opportunity to become a major player in the European "hydrogen economy" and export green fuels to Central European countries (Ikäheimo et al. 2018).

However, the development of a hydrogen economy depends on several factors, such as economic feasibility, future demand and supply, and the idea of becoming a hydrogen export region is subject to uncertainties. The availability of renewable energy sources for hydrogen and green fuel production is an important factor for the success of the energy transition. Different expansion pathways result in huge differences regarding the capacity of electrolysis. The status quo shows different regional conditions but high potential in Norway, Finland, Sweden, and Denmark (Pedersen et al. 2022) Gea-Bermúdez et al. (2023) show a range of 6–357 GW of offshore electrolysis capacity by countries in the North Sea and Baltic region. Gea-Bermúdez et al. (2023), Ikäheimo et al. (2018), and Karlsson and Meibom (2008) state that wind (onshore and offshore) and hydropower are the most relevant renewable energy sources on a Nordic scale to produce hydrogen and green fuels.

The national conditions reveal differences within the Nordics. Child and Breyer (2016) analyse the decarbonization of the Finnish energy system. Onshore wind energy and PV will be the main contributors, and Finland is the only country in the Nordics with a share of nuclear power in the long term. Bramstoft and Skytte (2017) focus on the decarbonization of the Swedish energy sector and Lund et al. (2022) of the Danish energy sector. Both countries offer good onshore wind conditions with relevant contributions of biomass. In the long term, a limited offshore wind contribution is possible while the nuclear capacity in Sweden decreases. Norway has a different starting position as the power sector is already renewable due to abundant hydropower capacity (Pedersen et al. 2022) and an expansion of offshore wind and PV (Haaskjold and Pedrero 2023).

The investigations by Lund et al. (2022), Karlsson and Meibom (2008) and Bramstoft and Skytte (2017) highlight the opportunity to use the biomass potential in the production of synthetic fuels. Biomass offers either the chance to process hydrogen by adding biomass-based CO_2 or directly in biofuel production. Drysdale et al. (2019) and Lester et al. (2020) show uncertainty about the future contribution of biomass and discuss the competition with hydrogen for renewable fuel production.

Pedersen et al. (2022) discuss infrastructure as a prerequisite for exports or imports of energy. The realisation of the potential to export renewable energy is uncertain. The existing interconnections between the Nordics and Europe limit the chance to import or export hydrogen and require further investments. The Swedish infrastructure lacks a country-wide gas transmission grid. The gas grid in the southwest is linked to Denmark and is seen as the starting point for further development. Norway, as a major source of European natural gas supply, already has an interconnected energy infrastructure that generates opportunities for future hydrogen exports. Together with Denmark, the country offers potential storage capacities for hydrogen in the form of salt caverns. The Danish natural gas grid has existing connections to central Europe and can function as a link for the Nordics to supply

European demand (Pedersen et al. 2022). In this context, the Danish grid operator Energinet participates in the current discussions on a hydrogen backbone (Creos et al. 2021).

2.2 Example 1: Analysis with DTU Balmorel Europe

The Balmorel model is a technology rich, large-scale energy system model, which has been applied in many parts of the world (Wiese et al. 2018) The model is driven by exogenous inputs on demands in different sectors for electricity, heat, and fuels, including hydrogen and other alternative fuels. For some sectors, the hydrogen demands are given directly, for others the demands are determined endogenously based on competition with other energy carriers, and associated technologies and infrastructures, e.g., for the generation of peak electricity. For the analysis presented below, a least-cost optimization has been applied for the entire EU with investments allowed in electricity and hydrogen transmission grids and storages, as well as generation units. Technology costs on investment and operation are mainly from the technology catalogues provided by the Danish Energy Agency (DEA 2021). Fuel costs, as well as a uniform CO_2 tax is based on the World Energy Outlook's Net Zero Energy scenario (IEA 2023).

2.2.1 EU Hydrogen Infrastructure in 2050

Kountouris et al. (2023) investigate the development of EU hydrogen infrastructure in a pan-European case study from 2030 to 2050. They analyse three main scenarios: (1) *Blue,* which allows for hydrogen production using steam methane reforming from abated and unabated natural gas as well as via electrolysis and imports of green hydrogen; (2) *Green*, which only allows hydrogen production from electrolysers and imports; and (3) *-Imports*, which also only allows hydrogen production from electrolysers but prohibits hydrogen imports from outside EU. The first two scenarios consider imports from Tunisia & Algeria, Morrocco, and Ukraine. In this section, we consider *grey* hydrogen as hydrogen produced using steam methane reforming (SMR) from unabated natural gas, *blue* hydrogen as produced using SMR from abated natural gas using CCS, and *green* hydrogen produced by electrolysers using electricity from the grid. Since we focus on the long-term developments in 2050, for simplicity, we do not consider the additional restrictions on electricity sourcing introduced by the Delegated Act on RFNBOs (EC 2023). In addition, the study examines how different cost assumptions for electrolysers and natural gas prices affect the balance between blue versus green hydrogen production. In the following, we extract the most important results for the hydrogen infrastructure in the Nordics. Iceland was not part of the study.

2.2.2 Hydrogen Demand Assumptions

The Balmorel model used in Kountouris et al. (2023) assumes a certain amount of hydrogen as model input. This demand needs to be fulfilled and drives the model's investments in a mixture of new hydrogen grids, repurposed natural gas grids, and electricity transmission. Therefore, it is important to carefully evaluate which and to what amount hydrogen demands are included.

They consider an EU hydrogen demand of about 10 Mt. (332 TWh) in 2030 and 53 Mt. (1767 TWh) in 2050. The exogenous demand input is based on the Hydrogen Backbone report (2021) and includes applications for ammonia synthesis, liquid fuels and high-value chemicals, high-temperature industrial process heat, and iron ore reduction using hydrogen directly (but not for residential heating). The Nordics are assumed to have a relatively low hydrogen demand compared to other Central and Western European countries with more industry.

Figure 1 shows the input of exogenous hydrogen demands in the left column, which are an assumption based on other reports and an input to the model, and in the right column, the endogenous hydrogen demand, which is additional demand derived within the Balmorel model. The endogenous hydrogen demand can be used for synthetic fuels for buses and trains and for peak power. Thus, for the Nordics in 2050, the model assumes a total demand of 3.3 Mt. (110 TWh) of hydrogen.

2.2.3 EU Self-Sufficiency

In the context of the recent political discussion about the heavy dependence on Russian natural gas (especially in Germany), Kountouris et al. (2023) investigate the

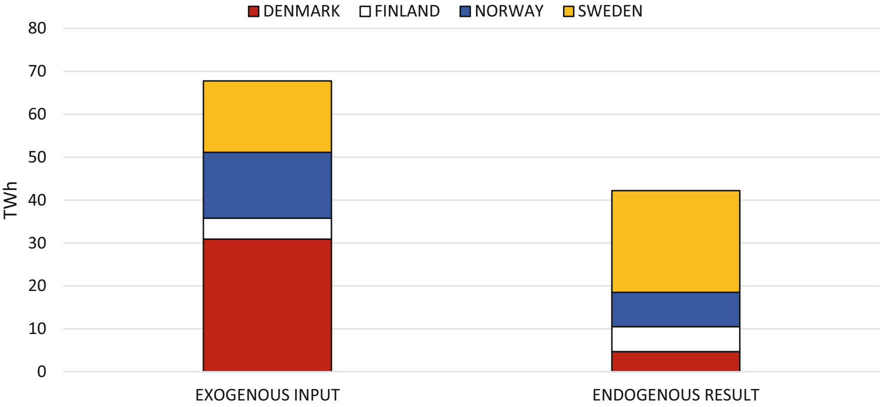

Fig. 1 Hydrogen demand in the Nordics in 2050. *Note:* The left column is based on exogenous input values and the right column results from the model. The values are identical for all three scenarios

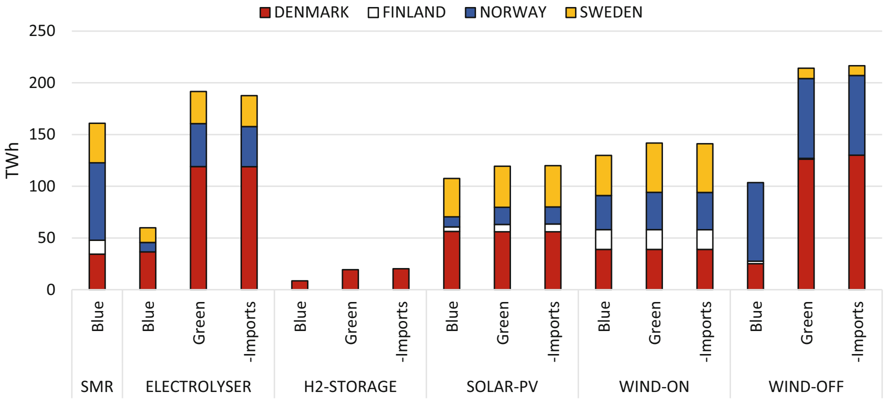

Fig. 2 Selected generation in the Nordics in 2050. *Note:* Scenario blue allows for hydrogen production using steam methane reforming (SMR) from abated natural gas, green only allows production using electrolysers, and -Imports disallows imports from outside EU (Color figure online)

impact of a self-sufficient EU without reliance on hydrogen imports from outside EU. They find that prohibiting hydrogen imports seems to have only marginal effects on the infrastructure of the Nordics (Fig. 2), whereas the main effects are seen in the South of Europe. For example, Italy that used to become a hydrogen corridor for imports from Northern Africa to Germany, significantly expands its hydrogen production capacity if imports are prohibited. Since the *Green* and *-Imports* scenario results are relatively similar, in the following, we illustrate only the *Blue* and *Green* scenarios.

2.2.4 Blue Hydrogen Production

The impact of blue versus green hydrogen production is still relevant in the context of the recurring debate on the role of carbon capture and sequestration (CCS) considering the importance for the Nordics, especially in Norway, and the large amount of 1.400 Mt/year of captured CO_2 that the European Commission considers in their modelling exercises using their JRC-EU-TIMES model (Blanco et al. 2018). We hence explore this, even though the European Commission with their Delegated Act (EC 2023) has for now settled on the use of renewable electricity and electrolysers to produce renewable hydrogen.

2.2.5 Generation and Storage Capacities

When hydrogen production is allowed by using steam methane reforming (SMR), the dynamics in the Nordics change significantly. Due to a carbon tax in the model

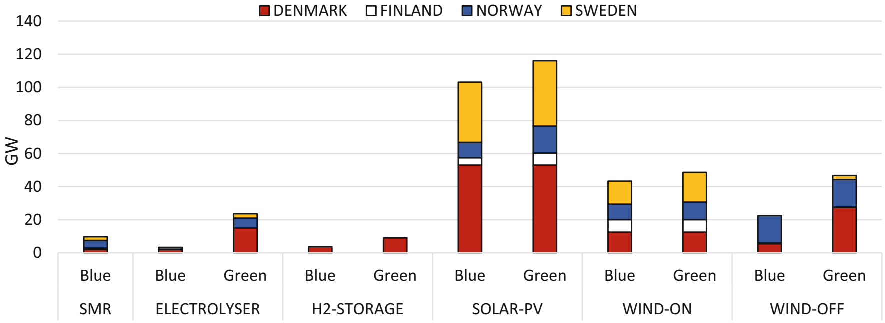

Fig. 3 Selected capacities in the Nordics in 2050. *Note:* Scenario blue allows for hydrogen production using steam methane reforming (SMR) from abated natural gas, and green only allows production using electrolysers (Color figure online)

(about 190 €/t CO_2 in 2050), only abated natural gas using CCS technologies is used in the Nordics. Kountouris et al. (2023) assumes a natural gas price of 10.87 €/MWh in 2050 based on the $3.8/MBtu of the Net Zero emissions scenario of the World Energy Outlook 2022 (IEA 2022).

Figure 3 shows that with small SMR capacities, especially in Norway, substantial amounts of blue hydrogen replace what would have been green hydrogen using electrolysers (Fig. 2) In addition, this also substantially reduces the need for renewable energy and hydrogen storage (Fig. 3) Most importantly, it shifts the centre of hydrogen production within the Nordics from Denmark to Norway, strengthening the role of natural gas producers in the energy transition. Due to the lower capacity factors of solar PV compared to wind (see generation in Fig. 3) and the assumptions of limited onshore wind potentials based on public acceptance, the strongest impact is on (relatively expensive) offshore wind investments, which decrease significantly, especially in Denmark and Sweden (Fig. 3).

2.2.6 Transmission Infrastructure

Figure 4 shows that the *Blue* scenario also affects the transmission infrastructure, namely electricity transmission lines (EL) and hydrogen pipeline infrastructure (H2). The *Blue* scenario decreases the overall need for hydrogen infrastructure in the Nordics from 45 to 32 GW. On the other hand, the need for electricity transmission lines remains approximately the same in both scenarios, at 68 GW.

2.2.7 Electricity and Hydrogen Exports

The Nordics mainly provide hydrogen to central Europe by exporting to Germany (DEU) and the Netherlands (NLD) via Denmark (DNK) or Norway (NOR). Figure 6

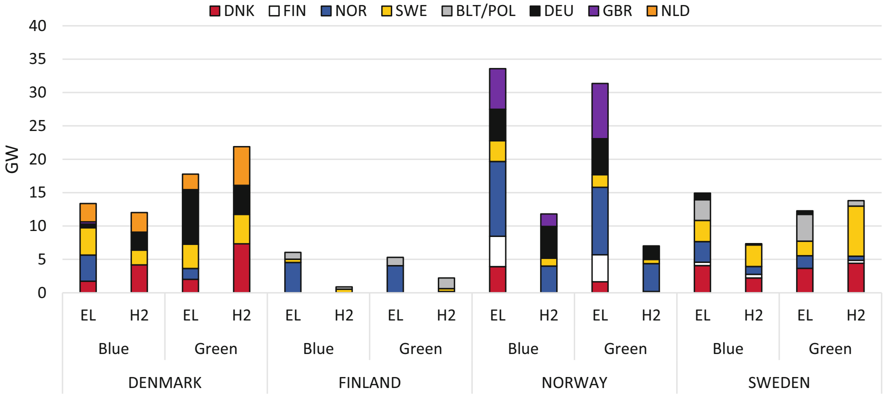

Fig. 4 Selected electricity (EL) and hydrogen (H2) transmission infrastructure in the Nordics in 2050. *Note:* Scenario blue allows for hydrogen production using steam methane reforming (SMR) from abated natural gas, and green only allows production using electrolysers. *DNK* Denmark, *FIN* Finland, *NOR* Norway, *SWE* Sweden, *BLT/POL* Baltic countries + Poland, *DEU* Germany, *GBR* Great Britain, *NLD* Netherlands (Color figure online)

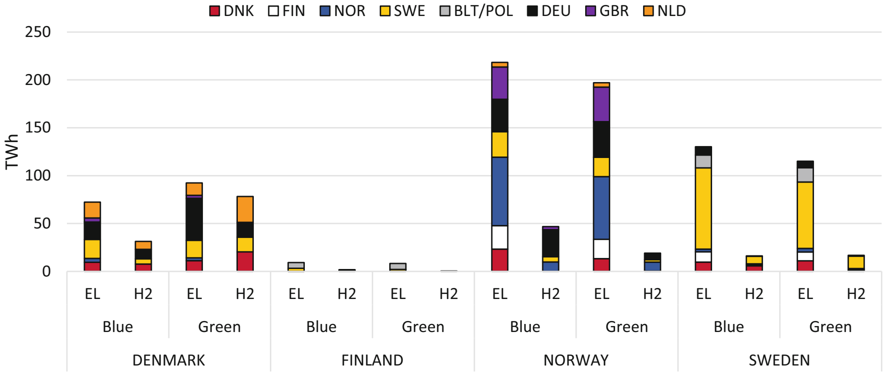

Fig. 5 Electricity and hydrogen exports from and within the Nordics in 2050. *Note:* Scenario blue allows for hydrogen production using steam methane reforming (SMR) from abated natural gas, and green only allows production using electrolysers. *DNK* Denmark, *FIN* Finland, *NOR* Norway, *SWE* Sweden, *BLT/POL* Baltic countries + Poland, *DEU* Germany, *GBR* Great Britain, *NLD* Netherlands (Color figure online)

also shows considerable trade flows within the Nordics and within the Nordic countries considering the trade between the different bidding zones of each country. In the *Blue* scenario, Norway becomes the main exporter to Germany and significantly increases its hydrogen exports (Fig. 5). At the same time, in the *Blue* scenario, Denmark reduces its exports to Germany, the Netherlands, and Sweden. Overall, however, the hydrogen exports from the Nordics stay approximately the same, around 71 TWh in 2050.

On the other hand, the electricity exports from the Nordics are considerably higher than the hydrogen exports, with around 265 TWh in all scenarios (Fig. 5) The *Blue* scenario also affects electricity exports as more electricity is exported from Norway and Sweden. The dynamics of the *Green* scenario are driven by the additional offshore wind generation (Fig. 3) which is mainly added in Denmark and to some extent in Sweden.

2.3 Example 2: Analysis with EML TIMES-NEU Model

The TIMES Northern Europe (TIMES-NEU) is based on the open source ON-TIMES (https://github.com/NordicEnergyResearch/NCES2020) The number of green fuels and production technologies have been expanded, heavy industry is more detailed, with more green options and trade connections to surrounding countries (Fig. 6).

TIMES-NEU Characteristics

- Partial equilibrium least cost system optimising and investment model.
- Main driver to the model is official economic projections on sector level and projections of population.
- 56 time slices a year, representing different seasons, day/night, and critical load situation—solved in 5-year steps until 2050.
- In Norway, Denmark, Sweden, Germany, and Poland all sectors included—internal trade with eight most important energy carriers among these core countries.
- With the surrounding countries (light blue) power trade between connected regions are modelled with price profiles to main model countries.
- UK, Belgium, and Netherlands—also trade with the eight energy carriers based on price profiles and potentials.
- Main model countries (darkest blue in the map) can also trade more than 40 energy carriers (fossil fuels, bio- and electro fuels, biomass, and electricity) with the global market represented with projected global market fuel prices (Fig. 7).

Important assumptions are as follows:

- National climate targets are assumed respected in the five main countries.
- Existing and projected CO_2- and energy taxes are included for the five main countries.
- Exogenous electrolyser capacity introduced according to "realistic" plans.
- Stop for import of green fuels and biomass to the main model area from 2040 (excluded from this is ammonia and hydrogen) to reflect impact from possible future EU regulation, e.g., extended EU Carbon Border Adjustment Mechanism (CBAM).

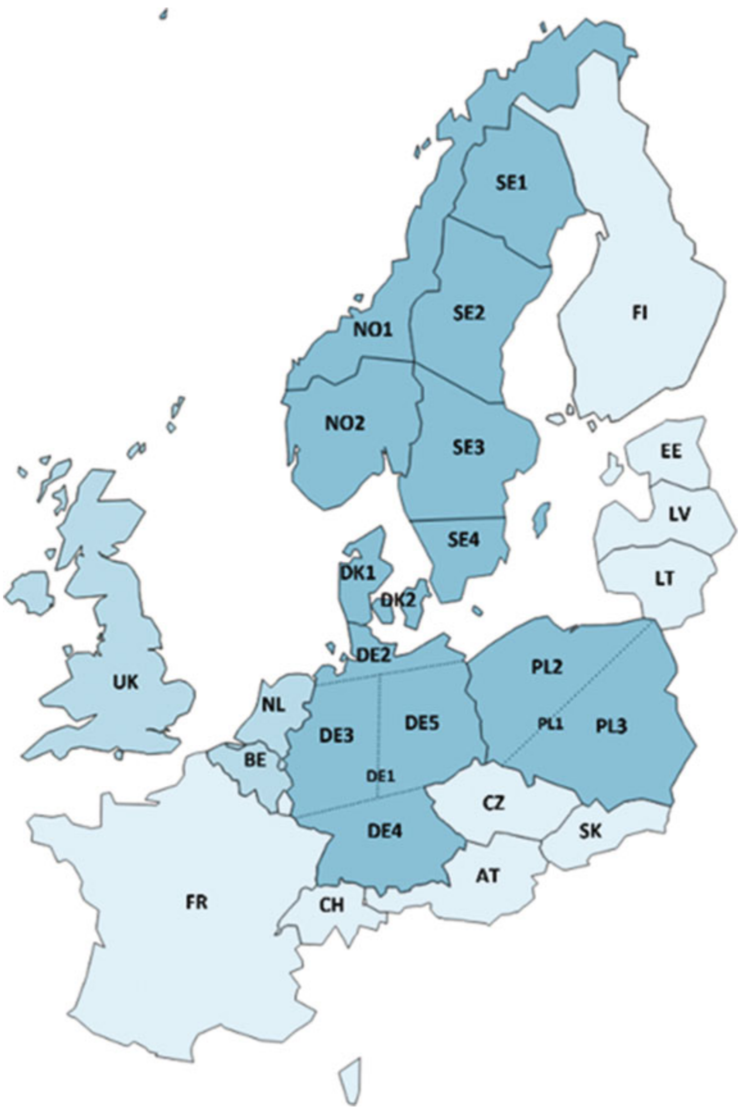

Fig. 6 Geographical area and model regions of TIMES-NEU

- Reduction over time in available biomass for energy. Biomass resource in the main model countries is reduced by around 20% in 2030 and 40% in 2050.
- External/exogenous green hydrogen demand projections for UK, Belgium, and Netherlands
- For non-energy purpose (mainly chemical industry) fossil fuels are assumed to be faced out linearly from 2030 to 2050.

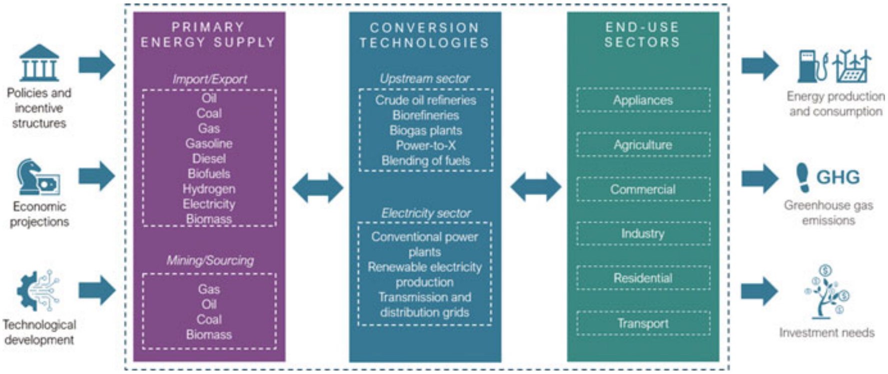

Fig. 7 Illustrative structure of the TIMES-NEU. The model includes primary supply of fuels, upstream sector, power and heat sector, and detailed modelling of all end-use sectors

2.3.1 Future Demand for Green Fuels

The demand for green fuels found in TIMES-NEU is a result of the competition between the different fuels, technological options in each sector and a global market with competing prices on all energy carriers. In the full modelling period, the five main countries can trade eight energy carriers (electricity, e-methanol, b-methanol, e-ethanol, b-ethanol, ammonia, wood chips, and wood pellets), among each other, only limited by transmission capacity (pipes, power lines etc.) With the UK, Belgium, and Netherlands the main countries can also trade the eight energy carriers and with the rest of the surrounding countries electricity can be traded between countries with shared borders. All +40 energy carriers can be traded with global market, restricted by the implemented trade constraints.

In Fig. 8 it is very clear when the import constraint on biomass and biofuels kicks in (2040), this means biofuels are replaced by e-fuels. The demand for green hydrogen as a fuel is only manifested at the end of the scenario period when the steel industry is converting.

The demand for green hydrogen in the UK, Belgium and Netherlands are based on an external analysis of their own possibility for producing fuels and their expected demand (Brinckmann 2023). The model then sees a potential export option to these countries based on their net demand and a related price. In particular, Belgium and Netherlands have a large chemical industry with a growing demand for green fuels in the future and there are big international harbours in the Netherlands which are imagined becoming fuelling hubs for international shipping.

Figures 9 and 10 shows which countries are producing the hydrogen used and traded among the countries in the model (and to the global market). The role Denmark potentially can play in this market is huge because of the wind resources in the North Sea and the central position with short distances to large consumers. So, this analysis shows that Denmark could deliver almost 50% of the needed hydrogen

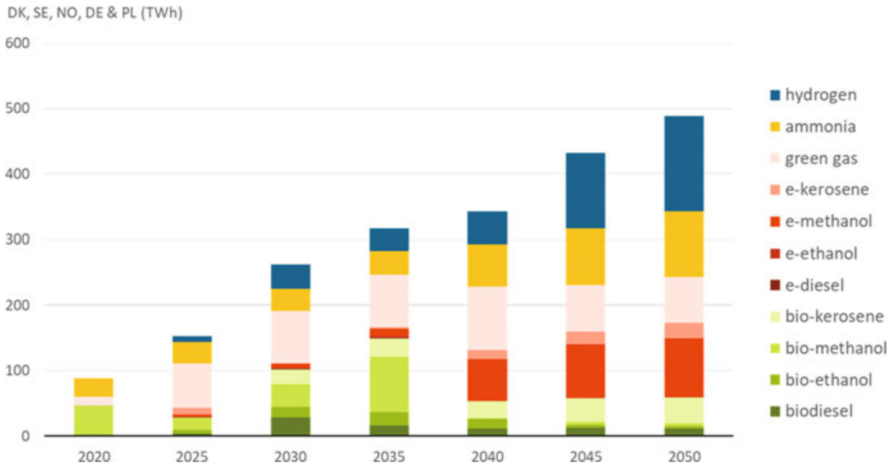

Fig. 8 Modelled demand for green fuels (bio and electro) in the fully modelled countries (Denmark, Sweden, Norway, Germany, Poland)—not including UK, Netherlands, and Belgium

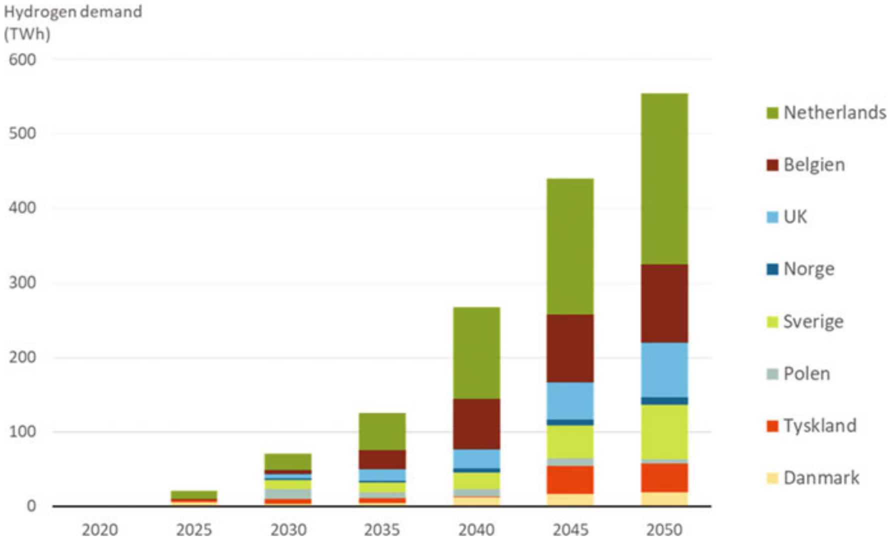

Fig. 9 Expected direct hydrogen demand in the larger model area. *Note:* This includes direct use in industry. The demand is endogenous decided by the model in Denmark, Norway, Sweden, Germany, and Poland while it is exogenous added to the model for Netherlands, Belgium, and UK

in the model area. Any mismatch between demand and production in the model area is balanced out by trade on the global market.

Surprisingly, to many, the model shows Germany as net exporter of green hydrogen until 2040 (Fig. 11) mainly due to already planned German electrolyser

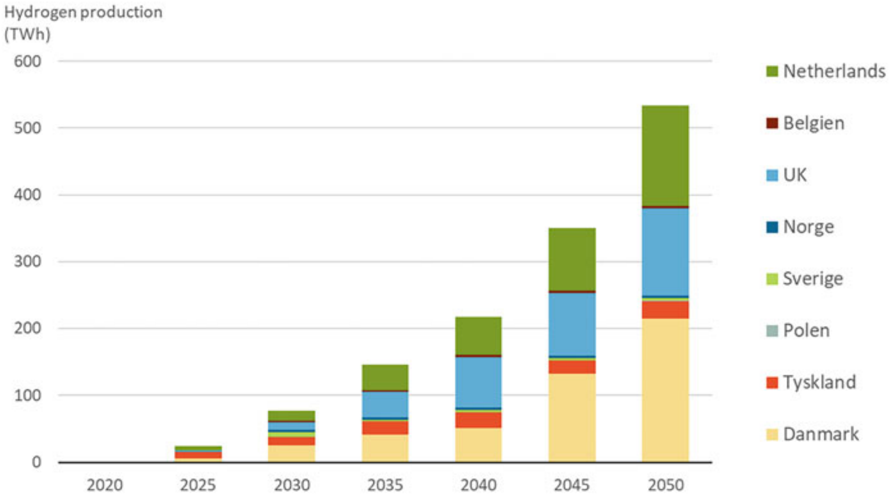

Fig. 10 Expected hydrogen production in the larger model area. *Note:* The production is endogenously decided by the model in Denmark, Norway, Sweden, Germany, and Poland while it is exogenously added to the model for the Netherlands, Belgium, and the UK

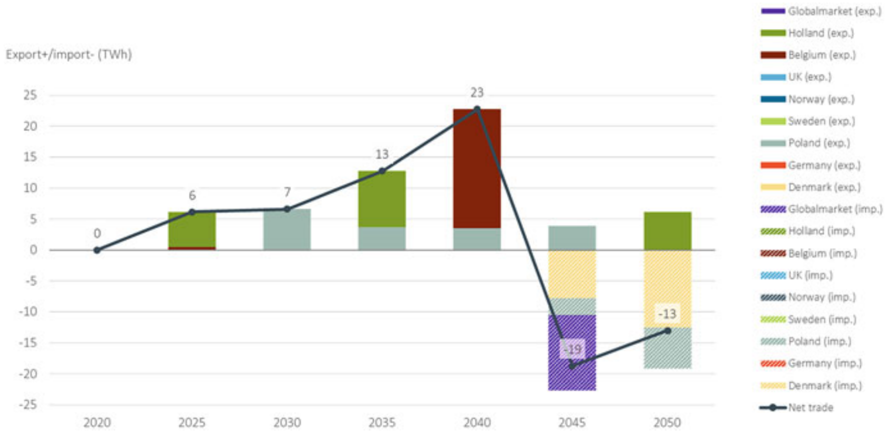

Fig. 11 Germany’s trade with green hydrogen

capacity and it is only when the steel industry switches from coal to green hydrogen and electricity in 2045 that their own production cannot keep up. This means a total replacement of the old steel plants with new HYBRIT plant types.

The Danish export of green hydrogen flows in two directions (Fig. 12). South, as expected beforehand, not in the beginning to Germany but to Belgium. Another flow is to Sweden which has a growing demand for green hydrogen for their chemical industry and for the green transition of their steel industry. Sweden cannot produce

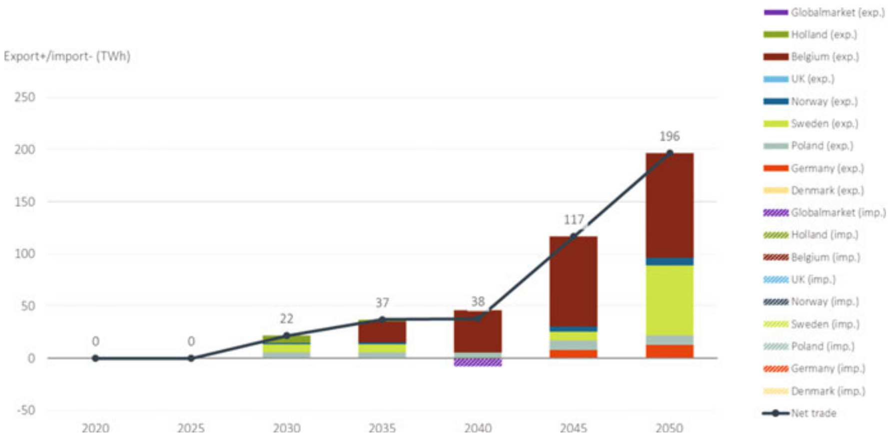

Fig. 12 Danish trade with green hydrogen

hydrogen as cheap as Denmark can in the North Sea and the model finds it cheaper to establish a hydrogen pipeline from Denmark to Sweden. The Swedish hydro power resources are limited, and Swedish offshore wind parks will have less FLH than wind parks in the Danish part of the North Sea, hence the production price of hydrogen is higher in Sweden.

These modelling results perfectly illustrate the uncertainty in the future market for green fuels. In this case the driver for Danish green hydrogen exports is an exogenous demand projection for UK, Belgium, and Netherlands not dynamically considering the competition from electrification and other fuels to green hydrogen in these countries. Another driver for hydrogen demand is the production of ammonia for the shipping and chemical industries and in the presented scenario the model imports all fossil and green ammonia from the global market hence no local production. The prices the model sees for production (including transport and handling) of ammonia in the Middle East, Northern Africa and Australia are cheaper than production in the model area. If this balance was switched and green ammonia was being locally produced, then the demand for hydrogen in the model area would almost double.

2.3.2 Development of Infrastructure

Taking a closer look at the infrastructure development needed to fulfil the energy demands, we should pay special attention to the energy islands. The TIMES-NEU model has the option to invest in three **energy islands** for Denmark in the North Sea, plus utilizing the nearshore resources of the island Bornholm. According to the agreement from the Danish Parliament from June 2020, the first phase of the North Sea islands will have a minimum capacity of 3 GW of offshore wind power, with potential for expansion to 10 GW offshore wind. The strategic environment assessment also includes a second phase in which a total of at least 10 GW of offshore wind power is established (phase one and two), but with the possibility of establishing a total of up to 40 GW (phase one and two) within the same area if the power per km^2 is increased.

The ambitious goal of building these energy islands is still under political discussion and will determine the position of Denmark as a hub for green hydrogen in Northern Europe.

The Nordic power sector will have to face a major transformation to accommodate the high electricity demand needed to produce green fuels in the future. The resulting power capacity of the Nordics more than doubles, from around 90 GW to 232 GW in 2020, as a result of the electrification of key industrial sectors and the increase in the use of green fuels in Europe.

These capacities will also be highly dependent on the position that the Nordics would take in the global market of green fuels. A key question to understand the needed expansion of the power system is: would the Nordics become self-sufficient to fulfil their energy needs or would they become net exporters of green fuels to central Europe?

The modelling results of TIMES-NEU shows that the high wind potential of the North Sea is utilized to produce hydrogen, mostly at the energy islands, and export it to central Europe. The offshore wind installed capacity in Denmark by 2050 reaches 10 GW mainland and 44 GW in the energy islands, summing to a total of 54 GW, almost reaching the renewable potential set in the model to 57 GW. The same case applies for Norway, that almost utilizes their full renewable potential of 9 GW, setting up 8.6 GW of wind offshore by 2050. Due to the less competitive wind resources in Sweden, the model only installs 10 GW of the potential 20 GW, and imports the hydrogen directly from Denmark, Norway, or the global market, as shown in Fig. 13.

Figure 13 shows the evolution of the offshore wind capacity and Fig. 14 the electrolyser installed capacity in the TIMES-NEU modelled regions. These results show that it is more profitable to build the electrolysers directly in the energy islands, where the wind potential is high, and then build pipelines to transport the hydrogen to the main consumption hubs. This result is highly dependent on the cost assumptions of building pipelines versus building power lines and setting up the electrolysers in the mainland.

Another key result is the first-mover effect. The country that makes the first move in installing enough electrolyser capacity will determine the market share it can take in the first years. The results from TIMES-NEU show that the buildout of the energy islands with the electrolysers, makes Denmark a first mover, taking a high share of the global market, competing with Germany until the German industry demands its own domestic production.

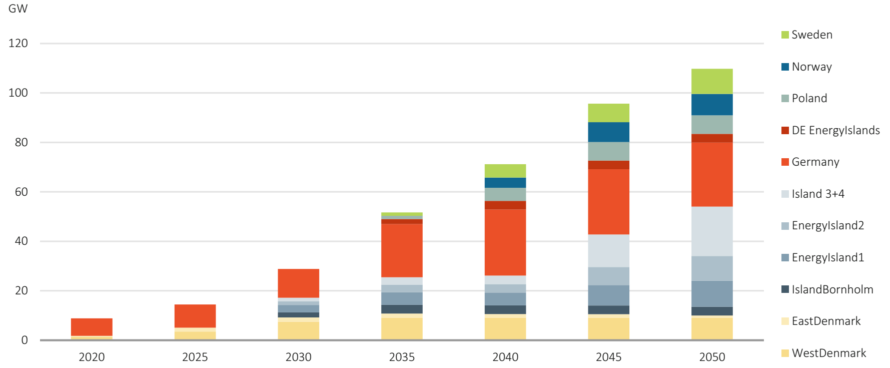

Fig. 13 Offshore wind capacity per country and energy islands. *Note:* "IslandBornholm", "EnergyIsland1,2" and "Island 3+4" are Danish islands, "DE EnergyIslands" are German islands

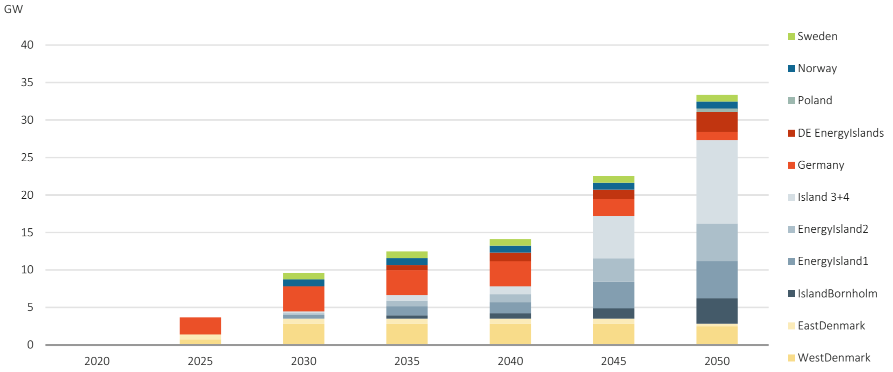

Fig. 14 Electrolyser capacity per country and energy islands. *Note:* "IslandBornholm", "EnergyIsland1,2" and "Island 3+4" are Danish islands, "DE EnergyIslands" are German islands

2.4 Take Aways from the Two Modelling Examples

Conclusions are clearly affected by the chosen methodology; are you back-casting demand for hydrogen from a fully decarbonised future or are you modelling the competition between energy carriers moving towards the same future? Back-casting tends to over-estimate the demand for hydrogen in short and mid-term (Balmorel case), while optimisation of the demand side tends to do the opposite, because it is not capturing early investments in plants (TIMES case).

The model area and boundary conditions are also important factors; what kind of trade options to the outside world has been established in the modelling framework?

Balmorel covers the power production and transmission system in all of Europe and potential production and export of green hydrogen from Northern Africa. This makes the Balmorel model suitable for analysing the competition in production of green hydrogen between different geographical areas and hence where to build hydrogen pipelines and where to expand renewable power capacity and transmission lines. The TIMES model has a detailed modelling of all end-use sectors and is therefore strong in analysing which sectors are going to use green hydrogen (and other green fuels), for what and from when. Obviously, combining the two models in one consistent analysis would improve the results and strengthen conclusions. This has not been possible to do for this chapter but there is an ongoing Danish research project wherein it will be realised.

3 How Is the Green Fuel Revolution in the Nordics Affecting SDGs?

The green fuel revolution has obvious advantages from a climate point of view by contributing to replacing fossil fuels. But what impacts, positive and negative, can the development of renewable electro fuels have on other sustainability goals and targets in a system perspective? To answer this question the United Nations Sustainable Development Goals (SDGs) framework has been used. There are 17 SDGs, and each SDG has several targets (in total 169 targets) The SDG Impact Assessment Tool (GMV and Chalmers 2023) has been used to screen the most relevant sustainability aspects affected by electro fuel production and their replacement of fossil fuels. The results are shown in Table 1. Biomass based fuels are not included in the assessment.

The most obvious direct **positive impact** of electro fuels is the potential reduction of greenhouse gas emissions through the replacement of fossil fuels (SDG 7 and 13). Although the production of electro fuels comes with upstream emissions, these can be low compared to the fossil fuels they replace. As an example, Hansson et al. (2023) calculated greenhouse gas performance of several renewable transport fuels, including electro fuels. The results show emission factors of 0–20 g CO_{2e}/MJ compared to 94 g CO_{2e}/MJ for their fossil counterparts. The emission factors of fossil fuels are based on the reference given by the EU Renewable Energy Directive. The emission factor of electro fuels varies depending on for example, the type of electro fuel, and assumed emission factor for electricity. The estimates above assume that the electro fuels meet the criteria set out in the EU delegated acts on methodology for renewable fuels of non-biological origin (RFNBOs), which means a very low electricity emission factor. To assure a climate benefit of electro fuels, the electricity must have very low climate impact. Other direct positive impacts include upgrading the industry to increased sustainability (SDG 9), transition of the transport sector and reduced environmental impact of cities (SDG 11). Indirect positive impacts include job creation in the Nordic countries (SDG 8) and potentially more efficient use of natural resources (SDG 12).

Table 1 Summary of relevant SDGs for electro-fuel production

SDG	Overall impact	Motive	Link to energy system model results
1. No poverty	Indirect negative	Risk that industrial countries exploit resources in developing countries	Development in total system cost of the energy system and its share of GDP
6. Clean water and sanitation	Direct negative	Electro fuels will require large amounts of clean water (for hydrogen production through electrolysis of water)	Amount of electro fuels produced and used
7. Affordable and clean energy for all	Direct positive	Mainly positive impacts. Renewable fuels replace fossil fuels. At the same time a lot of electricity is required which may lead to direct and indirect negative environmental impacts as well as competition of energy for other purposes	Projection of green fuel and electricity prices
8. Decent work and economic growth	Indirect positive	The production of renewable fuels will create new and potentially more jobs in the Nordics (although there is extensive refinery industry currently, the production of green fuels may cover a larger part of the global fuel demand and thus lead to more jobs)	Amount of installed energy related capacities in the period
9. Industry, innovation, and infrastructure	Direct positive	The purpose of the green fuel revolution is to upgrade industry to increased sustainability	New synergies between energy sector, industries, and other end-users
11. Sustainable cities and communities	Direct positive	Renewable fuels support the transition of the transport sector to increased sustainability and reduce the environmental impacts of cities. Conflicting targets may be potentially increased energy prices	Speed of transition in the different economic sectors
12. Responsible consumption and production	Indirect positive	Primarily assumed positive impact on efficient use of natural resources due to reduced demand for fossil resources. There may also be negative effects on specific targets	Projected future use of biomass and other resources for energy and fuel production
13. Climate action	Direct positive	Renewable fuels will replace fossil fuels and thus contribute to reduced climate impact (provided that the electricity required has low climate impact)	Development in GHG emissions from the energy sector
14. Life below water	Indirect negative	Probably low impact. The water demand for electrolysis might affect this SDG, although more relevant for SDG 6	Water consumption for energy plants

Note: There may be both positive and negative impacts on a specific SDG. The table shows the impact that was considered most important in the screening process

The production of electro fuels requires large amounts of clean water, which has a direct **negative impact** on SDG 6. In areas with scarce water resources there may be solutions such as desalination of sea water or cleaning of wastewater. Other negative impacts are mostly indirect and related to risks that industrial countries exploit resources (e.g. critical materials) in developing countries (SDG 1), negative environmental impacts due to increased electricity demand (SDG 7), competition of energy for other purposes (SDG 7) and potentially increased energy prices when electricity demand increases (SDG 11).

4 Key Challenges and Social Concerns

For the Power-to-X visions to become reality, a willingness-to-change is needed. The key challenges can be summarized into (1) the need for bridging a price gap and (2) a deviating focus, from energy-transition into decarbonization, with consequences for the build-out and social acceptability of PtX.

4.1 Price Gap: A Battle of Colours

With the normalization of natural gas prices, blue hydrogen is currently (2023) more than 50% cheaper than green hydrogen (Bhashyam 2023) While green hydrogen is expected to outcompete grey hydrogen by 2030 due to taxation on emissions, blue hydrogen will be more difficult to out-battle as the impact of carbon taxation is small. Green hydrogen is expected to become cost-competitive with blue hydrogen given various impact factors, like technology maturity, build-out of renewable energy, the EU methane regulation EU ETS, and tax regimes, at least within the EU.

The future of green hydrogen consumption in the EU has been determined by the Renewable Energy Directive III, where the hydrogen consumption in the industry must fulfil a minimum requirement of 60% renewable hydrogen by 2035. When looking at other continents, the picture looks different. In the US, blue and green hydrogen seem to be considered as renewable hydrogen and subsidies target both technologies (upon decision of the Treasury department by the end of 2023) Looking to Asia, specifically China, where natural gas is scarce, green hydrogen is expected to be the most cost-effective. Chinese technology could also become one of the key drivers for technology advancement within electrolysers (IEA 2023).

4.2 Delays and Challenges

The combination of an un-bridged price gap and the intensified focus on decarbonization has resulted in general delays for announced PtX Projects. Figure 15

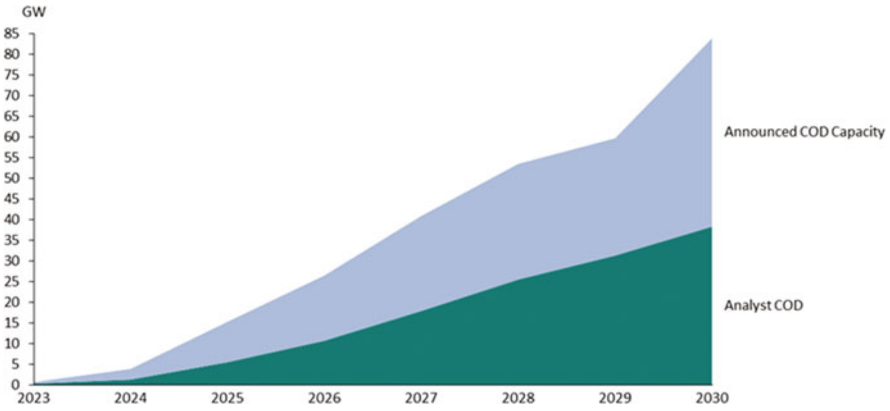

Fig. 15 Commercial Operation Date (COD) based on the announced project pipeline of developers compared to the expected pipeline PtX capacity of analyst when incorporating offtake markets, country of development and development consortium (Brinckmann 2023)

outlines forecasted delays in the realization of European PtX projects in comparison to announced realization date, considering key parameters for commercial assessment of project feasibility (Brinckmann 2023).

Another reasoning for project delays can be found in the missing offtake commitment from the industry. Although the offtake potential has been thoroughly investigated, and national plans and strategies for PtX have been initiated (e.g., the Danish PtX Strategy 2021), there is still a lack of commitment from targeted off takers, e.g., in the steel industry. While the political ambitions and targets in the EU are getting more and more clear, the political landscape in other parts of the world is more uncertain, e.g., in the US with the upcoming presidential election.

Finally, local opposition adds a further layer of complexity and uncertainty. Local community concerns over PtX are still under-researched, but likely to emerge with the prospect of accelerated PtX upscaling. Renewable energy facilities already face considerable local resistance in the Nordic countries (European Commission et al. 2022; Energy Monitor 2022; MX Underwriting Europe et al. 2022; Kirkegaard et al. 2020). This can delay the build-out of PtX. Further, PtX facilities are likely to produce public concerns over their siting: For instance, PtX facilities are so far classified as industrial facilities in Denmark, and therefore to be placed in industrial zones. Since the Danish PtX Strategy encourages renewable energy and PtX facilities to be co-located to make best use of the electricity network, this has potential to create local community concerns in urban areas (Klima-, Energi- og Forsyningsministeriet 2021). At the same time, the potential of PtX facilities to turn rural areas into industry-like areas, if sited there, is foreseen to produce local concerns due to a disrupted 'sense of place'. Eventually, public concerns are also likely to emerge around safety (e.g., explosion risks), the distribution of costs and benefits (e.g., compensation schemes). Meanwhile, there is potential to also create local value, e.g., through job-creation, compensation for loss of value of property, and funds to develop local communities. There is therefore an urgent need to strengthen public engagement and participation of local communities in the plans for PtX, to foster **social acceptance**.

4.3 Renewable Electricity: It Needs to Happen Sooner Rather than Later

A large amount of renewable electricity is needed to produce green hydrogen in the targeted amounts. Additional renewable energy installations are not an option but a prerequisite for realizing the PtX targets. The Danish Energy Agency has, for instance, projected the consumption of electricity in 2050 will be five times as much as it is today. This is almost entirely due to PtX and this electricity needs to come from renewable sources (DEA 2023). While additional capacities are needed, it is also beneficial for countries to add capacity to existing electricity-generating assets. With an estimated timeline of 3–4 years for a 1 GW electrolyser facility to go from financial investment decision (FID) to commercial operation, additional renewable electricity is needed sooner rather than later.

4.4 Willingness-to-Change: The Carrot and the Stick

Although PtX technology is not a new invention, it has failed to achieve a commercial breakthrough. Much of this is due to the fact that it is an expensive way to produce hydrogen and its derivatives compared to current production methods, which are predominantly based on natural gas. For the vast potential to be realized, it requires political will through regulation, funding, and technological maturity. Here the tendency in the EU is to use the stick rather than the carrot, which is reflected in the regulations governing the area, as outlined below:

4.4.1 Political Willingness

In recent years, the EU has worked hard to create an environment encouraging investment in sustainable solutions (the ‘carrot’) After years of waiting for a definition of renewable hydrogen, it finally arrived in June 2023 (Commission 2023), including rules for electricity generating assets, geographical location, and time correlation between electricity sourcing and hydrogen production. While this publication has been welcomed, the primary EU legislation on renewable energy in the industrial and transport sectors is still pending, and the final transposition of EU legislation into national law will not be completed until the summer of 2025. The lack of certainty in the legislation creates poor conditions for investment, which is one of the reasons why only a few projects are taking a final investment decision.

4.4.2 Funding

Funding for green hydrogen-based products has slowly started to pick up. The EU invests in PtX production through the European Hydrogen Bank and the Innovation Fund (CINEA 2023) programs. At a national level, Germany is leading the way in funding projects with several initiatives, to support hydrogen production and stimulate the off-take sector, e.g., the CCfD mechanism and H2Global (BMWK 2023). Denmark has been focusing on supporting the production side (but not the demand side), e.g., through the Danish tender for Power-to-X capacity. The winners have a period of four years to develop and install their PtX equipment and to start the production of green hydrogen. The total amount of support available was 170 Mio. EUR (Energistyrelsen 2023). While European countries have made it clear that they are keen on PtX, the process has a long timeline with uncertainties regarding budget and scale, and a vast funding gap, which remains to be filled. The current funding budget for PtX in Europe is ~EUR 22 billion, which, according to the industry, is far from the funding required to meet the targets.

4.4.3 Technology Maturity

The offtake market has expressed interest and a positive attitude towards hydrogen-based products since the products will be required to meet the sustainability requirements placed on all industries by the Renewable Energy Directive III, ReFuelEU Aviation, and FuelEU Maritime. However, PtX is an expensive production method, which requires some industries to invest in new technology and equipment to adapt to hydrogen. This leads to a possible lock-in scenario for off-takers when investing in equipment. Many industry players are waiting for others to take the first step and lead the way.

5 Conclusion

This chapter has been diving into the uncertainties of predicting the future demand for green hydrogen and other green fuels and what role the Nordic countries could play as their supplier. The role of hydrogen depends on the competition with other options for delivering energy services. In many cases hydrogen comes in as the last option because it is energy inefficient and so far, much more expensive than the close competitors: Electrification, biofuels, and blue hydrogen.

5.1 Export Potential from the Nordics

The Nordics offer great conditions to become an export region for hydrogen and green fuels. However, the region faces challenges regarding the ramp up of the hydrogen economy.

In all scenarios the Nordics become a net-exporter of hydrogen and electricity. If blue hydrogen is accepted then Norway will be the main producer, while if there is no market for blue hydrogen, then Denmark is in a leading position to become the main producer of green hydrogen. However, it is uncertain how this export market will split between Germany, Belgium, and Netherlands. The Nordic countries' export options seem not to be sensitive to import of hydrogen from northern Africa or southern Europe as these will rather out compete electrolysers in south and central Europe.

5.2 Need for Ramping Up Wind, PV, Electrolysers, and Infrastructure

A key aspect is the expansion of renewable capacities. The focus will be on offshore wind and PV as the expansion of onshore wind is restricted, e.g., due to public acceptance. The whole North Sea and Baltic region offers the potential of 3–357 GW of electrolysis, but this requires an expansion of offshore wind and PV production with a factor 20 compared to today.

5.3 Political Decisions and Regulation

The success of green e-fuel production in the Nordics depends on future policies for import of biomass and biofuels to the EU and the ETS securing a phase out of fossil fuels in all sectors. The end-use sectors need an early price signal to invest in green fuel-based processes.

Some key policies that can drive the demand for e-fuels:

- Will the countries ratify and respect EU's Fit for 55 package and their national climate targets?
- What level will the CO_2 price reach and how fast?
- Will governments or the EU create subsidy schemes for green fuels?
- How big will the market be for PPAs and other offtake agreements in the coming years?
- Will there be any restriction on imports of biomass and biofuels to the EU?

5.4 Sustainable Development Goals

The implementation of hydrogen and electro fuels has direct positive impacts on several sustainable development goals (SDGs 7, 9, 11 and 13) but also indirect positive effects (on SDGs 8 and 12) There are however also potential negative impacts that need to be addressed (mainly linked to water demand for hydrogen production i.e., SDG 6 and linked to electricity production, i.e., SDGs 1, 7, 11).

5.5 Social Concerns

Renewable energy projects in the Nordic countries are facing local resistance, potentially causing delays in PtX development. Public concerns regarding safety issues and the fair distribution of costs and benefits, are anticipated. Despite challenges, PtX initiatives offer opportunities for local value creation, such as job opportunities and community development funds. Urgent action is needed to strengthen public engagement, ensuring the inclusion of local communities in PtX plans to foster social acceptance.

References

Bhashyam A (2023) 2023 hydrogen levelized cost update: green beats gray. BloombergNEF. https://about.bnef.com/blog/2023-hydrogen-levelized-cost-update-green-beats-gray/

Blanco H, Nijs W, Ruf J, Faaij A (2018) Potential for hydrogen and power-to-liquid in a low-carbon EU energy system using cost optimization. Appl Energy 232:617–639. https://doi.org/10.1016/j.apenergy.2018.09.216

Bramstoft R, Skytte K (2017) Decarbonizing Sweden's energy and transportation system by 2050. Int J Sustain Energy Plan Manag 14:3–20. https://doi.org/10.5278/IJSEPM.2017.14.2

Brinckmann (2023) Proprietary database on announced PtX projects in Europe. Brinckmann, Aarhus. https://brinckmanngroup.com/

Bundesregierung (2023) Fortschreibung der Nationalen Wasserstoffstrategie. NWS 2023. Bundesministerium für Wirtschaft und Klimaschutz (BMWK) As of July 2023, Berlin

Child M, Breyer C (2016) Vision and initial feasibility analysis of a recarbonised Finnish energy system for 2050. Renew Sust Energ Rev 66:517–536. https://doi.org/10.1016/j.rser.2016.07.001

Creos, DESFA, Elering, Enagás, Energinet, Eustream, FGSZ, Fluxys Belgium, Gas Connect, Austria, Gasgrid Finland, Gasunie, Gaz-System, Gas Networks Ireland, GRTgaz, National Grid, NET4GAS, Nordion Energi, OGE, ONTRAS, Plinovodi, Snam, TAG, Teréga (2021) Analysing future demand, supply, and transport of hydrogen, European hydrogen backbone. Gas for Climate, Guidehouse, Germany

Danish Government (2021) The Governments strategy on Power-to-X. https://ens.dk/sites/ens.dk/files/ptx/strategy_ptx.pdf

DEA (2021) Technology data for renewable fuels. Energistyrelsen. Danish Energy Agency. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-renewable-fuels

DEA (2023) Analyseforudsætninger til Energinet, J nr. 2023–2106. Danish Energy Agency. Microsoft Word - AF23 - Sammenfatningsnotat.docx (ens.dk)

Drysdale D, Mathiesen BV, Paardekooper S (2019) Transitioning to a 100% renewable energy system in Denmark by 2050: assessing the impact from expanding the building stock at the same time. Energ Effic 12:37–55. https://doi.org/10.1007/s12053-018-9649-1

Energimyndigheten (2022) Förslag till Sveriges nationella strategi för vätgas, elektrobränslen och ammoniak. Eskilstuna. Sweden. ISBN 978-91-7993-004-8

Energy Monitor (2022) How to overcome local opposition to wind projects, 18 May 2022. Accessed 6 Nov 2023. https://www.energymonitor.ai/corporate-strategy/how-developers-can-overcome-local-opposition-to-onshore-wind-projects/

European Commission (2023) Delegated regulation on a Union methodology for the production of renewable fuels of non-biological origin (RFNBOs). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R1184

European Commission, Directorate-General for Energy, Tallat-Kelpšaitė J, Brückmann R, Banasiak J et al (2022) Technical support for RES policy development and implementation—Simplification of permission and administrative procedures for RES installations (RES simplify). Interim report. Publications Office of the European Union. https://data.europa.eu/doi/10.2833/239077

Gea-Bermúdez J, Bramstoft R, Koivisto M, Kitzing L, Ramos A (2023) Going offshore or not: where to generate hydrogen in future integrated energy systems? Energy Policy 174:113382. https://doi.org/10.1016/j.enpol.2022.113382

GMV and Chalmers (2023) SDG impact assessment tool. Gothenburg Centre for Sustainable Development and Chalmers Institute of Technology. https://sdgimpactassessmenttool.org. Downloaded November 2023

Haaskjold K, Pedrero RA (2023) Long-term optimization of the Norwegian energy system under the influence of the European power market. In: 2023 19th international conference on the European energy market (EEM) presented at the 2023 19th international conference on the European energy market (EEM). IEEE, Lappeenranta, pp 1–6. https://doi.org/10.1109/EEM58374.2023.10161972

Haberl H, Beringer T, Bhattacharya SC, Erb K-H, Hoogwijk M (2010) The global technical potential of bio-energy in 2050 considering sustainability constraints. Curr Opin Environ Sustain 2:394–403. https://doi.org/10.1016/j.cosust.2010.10.007

Hansson J. Nojpanya P, Ahlström J, Furusjö E, Lundgren J, Gustavsson Binder T (2023) Costs for reducing GHG emissions from road and air transport with biofuels and electrofuels. IVL report C770, June 2023

IEA (2022) World energy outlook 2022. International Energy Agency, Paris, France

IEA (2023) World energy outlook 2023. International Energy Agency, Paris, France

Ikäheimo J, Kiviluoma J, Weiss R, Holttinen H (2018) Power-to-ammonia in future North European 100% renewable power and heat system. Int J Hydrog Energy 43:17295–17308. https://doi.org/10.1016/j.ijhydene.2018.06.121

Karlsson K, Meibom P (2008) Optimal investment paths for future renewable based energy systems—using the optimisation model Balmorel. Int J Hydrog Energy 33:1777–1787. https://doi.org/10.1016/j.ijhydene.2008.01.031

Kirkegaard JK, Cronin T, Nyborg S, Karnøe P (2020) Paradigm shift in Danish wind power—the (un)sustainable transformation of a sector. J Environ Policy Plan 23(1):97–113. https://doi.org/10.1080/1523908X.2020.1799769

Klima-, Energi- og Forsyningsministeriet (2021) Regeringens Strategi for PtX. https://kefm.dk/Media/637751860733099677/Regeringens%20strategi%20for%20Power-to-X.pdf

Kountouris I, Bramstoft R, Madsen T, Gea Bermúdez J, Münster M, Keles D (2023) A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production. https://doi.org/10.21203/rs.3.rs-3185467/v1

Lester MS, Bramstoft R, Münster M (2020) Analysis on electrofuels in future energy systems: a 2050 case study. Energy 199:117408. https://doi.org/10.1016/j.energy.2020.117408

Lund H, Thellufsen JZ, Sorknæs P, Mathiesen BV, Chang M, Madsen PT, Kany MS, Skov IR (2022) Smart energy Denmark. A consistent and detailed strategy for a fully decarbonized society. Renew Sust Energ Rev 168:112777. https://doi.org/10.1016/j.rser.2022.112777

Mortensen AW, Mathiesen BV, Hansen AB, Pedersen SL, Grandal RD, Wenzel H (2020) The role of electrification and hydrogen in breaking the biomass bottleneck of the renewable energy system—a study on the Danish energy system. Appl Energy 275:115331. https://doi.org/10.1016/j.apenergy.2020.115331

MX Underwriting Europe, Wind Europe, Fieldfisher, LEIRA (2022) Report "barriers to wind", Vienna, Austria

Pedersen JL, Pade L-L, Søyland S, Håkansson NC, Grue J, Christensen JD, Diab M, Georgiev I, Krogh A, Ivarsson Á, Meinert Cardel O, Schøn T, Jákupsstovu S, Ritonummi T, Partanen T, Þorvaldsson JAH, Fuglerud M, Hallonsten P (2022) Hydrogen, electrofuels, CCU and CCS in a Nordic context. Nordic Energy Research, Oslo

Sovacool B (2017) Contestation, contingency, and justice in the Nordic low-carbon energy transition. Energy Policy 102:569–582. https://doi.org/10.1016/j.enpol.2016.12.045

Wiese F, Bramstoft R, Koduvere H, Pizarro Alonso A, Balyk O, Kirkerud JG, Tveten ÅG, Bolkesjø TF, Münster M, Ravn H (2018) Balmorel open-source energy system model. Energ Strat Rev 20:26–34. https://doi.org/10.1016/j.esr.2018.01.003