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THE ROLE OF HYDROGEN FOR A GREENHOUSE GAS-NEUTRAL GERMANY BY 2045

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ABSTRACT

Germany's transition to greenhouse gas-neutrality by 2045 requires a dynamic change in all sectors of its energy system. Despite several studies already depicting possible pathways for this transformation, the role of hydrogen in this process remains unclear. In this study we utilize a combination of energy system models to examine the usage and production of hydrogen during this transition in detail. Our results show that 412 TWh of hydrogen are needed in the year 2045, mostly in the industry and transport sector. Particularly, the use of hydrogen in industry is essential as there are no cost-effective alternatives for achieving greenhouse gas neutrality. Furthermore, we illustrate that domestic hydrogen production through electrolysis provides 53% of the needed hydrogen in 2045 and the remaining share is imported from other European countries or Northern Africa via pipelines or ships. Additionally, seasonal storage of hydrogen and hydrogen gas turbines play an important role in balancing the intermittent nature of variable renewable energy sources. In summary, hydrogen usage and production are crucial for a greenhouse gas-neutral Germany and should be integral part of the transformation strategy.

Keywords: energy system modeling, greenhouse gas-neutrality, Germany, hydrogen demand, hydrogen imports

INTRODUCTION

In 2021 Germany adapted its Federal Climate Change Act [1] and committed itself to become greenhouse gas-neutral by 2045. Furthermore, greenhouse gas emissions shall be reduced by at least 65 percent by the year 2030 compared to 1990 levels. Thus, a rapid transformation of the entire German energy system is necessary. Besides a large expansion of renewable energy sources like wind energy and photovoltaics, energy efficiency measures and a direct electrification in the end use sectors, hydrogen can play an important role in a greenhouse gas-neutral energy system.

However, recently conducted studies show a wide range for the expected German hydrogen demand in 2045. Moreover, the share of hydrogen imports differs significantly in the various scenarios. Prognos et al. [2] expect a hydrogen demand of 265 TWh in 2045, which is mostly used for electricity and heat production. Additionally, they state that 64% of the hydrogen is imported, but without mentioning of the import countries and costs. In contrast, the German energy agency [3] predicts a higher demand of 458 TWh hydrogen in 2045, where the largest consumption originates from the industry sector. Furthermore, they forecast that only 13% of the hydrogen is produced domestically and most of the hydrogen is imported from other European countries, North Africa, Russia or Turkey. The scenarios conducted by the Fraunhofer Institute for Solar Energy Systems [4] show a range of 120 to 330 TWh hydrogen demand in 2045, but do, in contrast to other studies, not include the usage of hydrogen as a feedstock in industry. Depending on the investigated scenario most of the hydrogen demand stems either from the transport or the industry sector. In the Ariadne-Report [5] a wide range for the hydrogen demand from 100 to 600 TWh in 2045 is given, as different scenarios are investigated and different energy system models are utilised. While the largest hydrogen demand is consistently based in the industry sector, the hydrogen demand in all sectors varies significantly between the scenarios and models. Moreover, the import share of hydrogen greatly differs between the scenarios and models, but import countries and costs are not given.

This study provides a holistic analysis of the hydrogen demand, production and imports in a greenhouse gas-neutral Germany. We apply an integrated energy system model which includes all energy demand sectors and the demand for hydrogen as a feedstock. Furthermore, we discuss in detail sources and costs for hydrogen imports to Germany. Additionally, we show the role of long-term hydrogen storage for providing supply security in periods with low energy supply by wind energy and photovoltaics. While the previously mentioned studies investigate some of these aspects as well, to the best of our knowledge no study for a greenhouse gas-neutral Germany by 2045 discusses all aspects in detail and provides a complete view of the future role of hydrogen.

MODELING

In this study we use the model family ETHOS (Energy Transformation Pathway Optimization Suite), which was developed at the Institute for Techno-economic System Analysis (IEK-3) of the Forschungszentrum Jülich [6]. This model suite consists of models which represent energy systems in a high temporal and spatial resolution. The center of this analysis is the optimisation model FINE-NESTOR [7], which depicts the German energy system and analyses cost optimal transformation pathways to greenhouse gas-neutrality. This integrated energy system model represents the sectors energy, industry, buildings and transport in detail through an hourly resolved network of energy sources, transformation processes, storages and energy demands. The central boundary condition for this analysis are the emission reduction targets from the Federal Climate Change Act, which must be met by the optimisation model. Hydrogen import sources and costs are determined with the simulation model InfH2 [8], which models worldwide energy supply chains. It includes the entire value chain for hydrogen imports from electricity production, electrolyzers and ship transport to Germany. The resulting cost-quantity curve is then passed to the FINE-NESTOR model, which decides if it is cheaper to produce hydrogen in Germany or import it.

RESULTS AND DISCUSSION

Our results show that hydrogen plays an important role for a greenhouse gas-neutral Germany. Fig. 1 displays that already in the year 2030 104 TWh of hydrogen are used. This demand increases by 2045 to 412 TWh. Thereby, the industry sector is with 267 TWh the main consumer of hydrogen. A main demand arises from the usage of hydrogen as a feedstock in the chemical industry, where 112 TWh of hydrogen are used to produce methanol. This methanol in turn is converted to high-value chemicals, which are used in the plastics production. Moreover, 86 TWh of hydrogen are used in the steel industry to produce iron via direct reduction of iron ore. Sensitivity analyses show that the industrial hydrogen demand is robust, as there are no cost-effective alternatives to the usage of hydrogen in this sector.

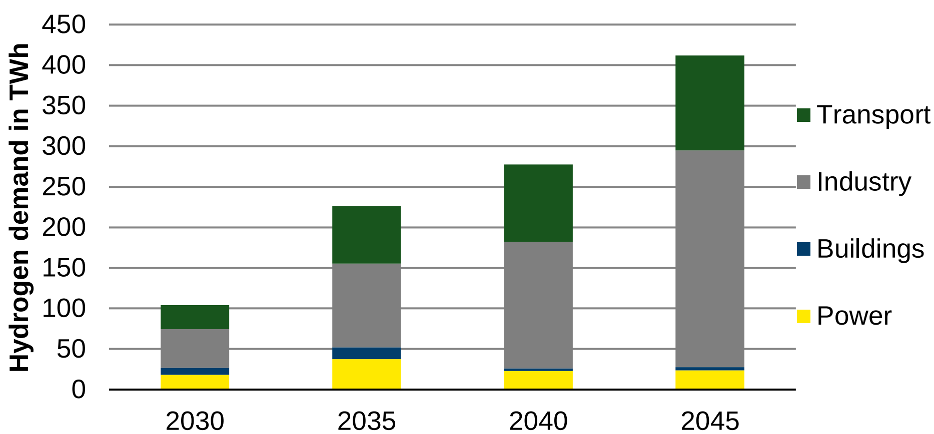

Fig. 1. Hydrogen demand by sectors in the transition to greenhouse gas-neutrality

In the transport sector 117 TWh of hydrogen are used, mainly for heavy trucks with fuel cells. Furthermore, hydrogen is used in the power sector to produce electricity in hydrogen gas turbines. This is especially important during dark doldrums, which describe periods with little energy generation from wind and solar power. In this study we consider a dark doldrum of two weeks in January, where only 10% of the capacity of wind energy turbines and photovoltaic plants is available for electricity production. To overcome this, period controllable power plants like hydrogen gas turbines or biomass power plants are used for meeting the electricity demand. Therefore, about 35.4 TWh of long-term hydrogen storage is needed to supply the hydrogen for the gas turbines and compensate for the seasonal variation of energy production from renewable sources. For this hydrogen storage salt caverns are used, which can mostly be created by conversion of existing natural gas storages.

Another source of flexibility for the energy system are the installed electrolyzers with a production capacity of 71 GW in the year 2045. They adjust their hydrogen production based on the available electricity produced by renewable sources and thereby help to balance the electricity production and demand. In the course of the transition, the full-load hours of centrally installed electrolyzers increase from about 2000 h in the year 2030 to about 2800 h in the year 2045. Fig. 2 shows that in the year 2045 electrolyzers produce 219 TWh of green hydrogen, the remaining 47% of hydrogen is imported from other European countries or Northern Africa via pipeline or ship. It must be noted, that in the year 2030 still about 26 TWh of hydrogen are produced by steam reforming, which is not depicted in Fig. 2.

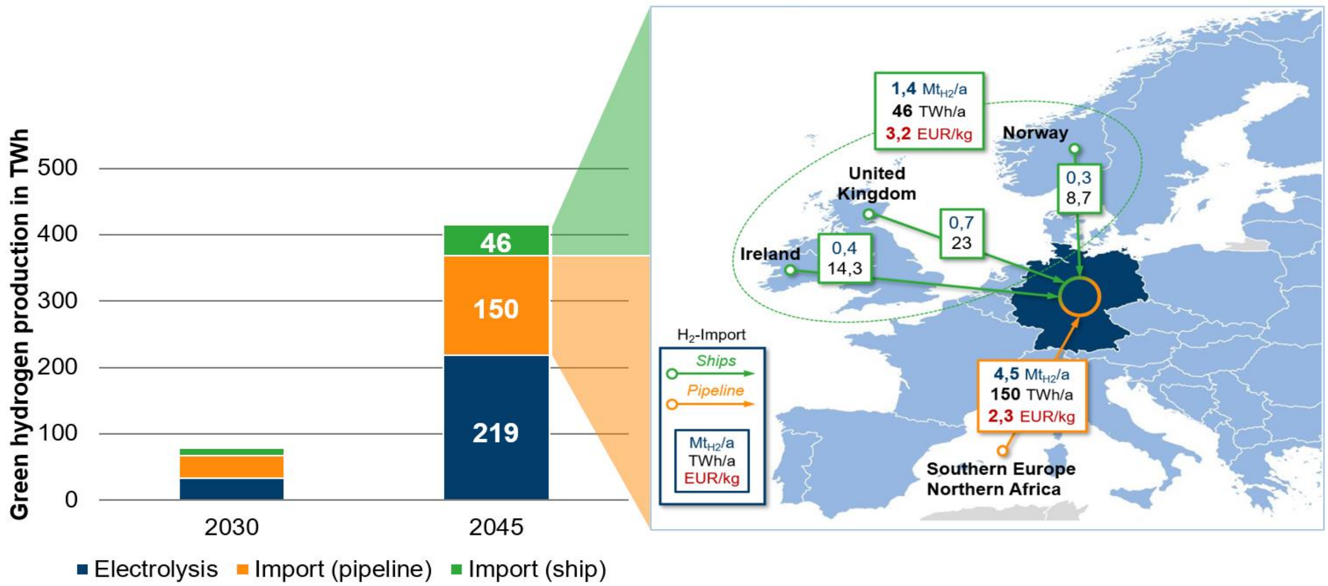

Fig. 2. Green hydrogen production and imports into a greenhouse gas-neutral Germany in the year 2045

With 150 TWh most of the hydrogen is imported via pipelines from Southern Europe or Northern Africa using mainly converted natural gas pipelines. Thus, the import costs of 2.3 €/kg are significantly lower than the average import costs of 3.2 €/kg for hydrogen imports from Northern Europe. This cost difference is mainly caused by the assumption that hydrogen from Northern Europe must be liquefied, transported by ship and then regasified in German harbors. If pipelines could be used to transport the hydrogen to Germany, the price difference would be smaller and more hydrogen could be imported.

CONCLUSIONS

Our study demonstrates that hydrogen is a central aspect of Germany's transition to greenhouse gas neutrality. Hydrogen is mainly used in the industry and transport sector, but also helps to balance the intermittent nature of photovoltaics and wind energy through long-term storage and flexible hydrogen gas turbines. Furthermore, this study shows that the target of the new German Federal Government of 10 GW electrolyzer capacity in 2030 [9] is not sufficient for the transformation, as according to our model results about 15 GW of electrolyzer capacity are needed in 2030. Thus, additional efforts must be made to meet 71 GW electrolyzer capacity in 2045, which is needed to produce 53% of the hydrogen domestically.

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