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The role of hydrogen for a greenhouse gas-neutral Germany by 2045

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HIGHLIGHTS

- 412 TWh of hydrogen demand in a greenhouse gas neutral Germany in the year 2045.
- Hydrogen usage is crucial for defossilization of chemical and steel industry.
- 47% of hydrogen is imported from other European countries and Northern Africa.
- 71 GW_{H2} of electrolyzer capacity in Germany with flexible operation.
- 35 TWh of hydrogen storage in salt caverns for security of supply.

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ABSTRACT

This paper aims to provide a holistic analysis of the role of hydrogen for achieving greenhouse gas neutrality in Germany. For that purpose, we apply an integrated energy system model which includes all demand sectors of the German energy system and optimizes the transformation pathway from today's energy system to a future cost-optimal energy system. We show that 412 TWh of hydrogen are needed in the year 2045, mostly in the industry and transport sector. Particularly, the use of about 267 TWh of hydrogen in industry is essential as there are no cost-effective alternatives for the required emission reduction in the chemical industry or in steel production. Furthermore, we illustrate that the German hydrogen supply in the year 2045 requires both an expansion of domestic electrolyzer capacity to 71 GW_{H2} and hydrogen imports from other European countries and Northern Africa of about 196 TWh. Moreover, flexible operation of electrolyzers is cost-optimal and crucial for balancing the intermittent nature of volatile renewable energy sources. Additionally, a conducted sensitivity analysis shows that full domestic hydrogen supply in Germany is possible but requires an electrolyzer capacity of 111 GW_{H2}.

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Introduction

In accordance with the Paris Agreement [1], Germany has committed itself to limit global warming to well below 2 °C compared to pre-industrial levels. Moreover, efforts are to be made to limit the global temperature increase to 1.5 °C, as this would significantly reduce the risks and consequences of global warming [2]. The Federal Climate Change Act [3], which was amended in the year 2021, takes this responsibility into account and obligates Germany to become greenhouse gas-neutral by the year 2045. Thus, a rapid and thorough transformation of the entire German energy system is necessary. Current trends show, that hydrogen will likely play a key role in the global energy transition towards carbon neutrality [4]. Therefore, the German government states in its national hydrogen strategy [5] that hydrogen will be a key element for a successful energy transition and the German transformation towards greenhouse gas neutrality. However, the allocation of the hydrogen demand to the different sectors of the German energy system remains unclear. Furthermore, it is not specified how the hydrogen will be supplied and stored.

Studies, which investigate the transformation of the German energy system towards Greenhouse gas neutrality until the year 2045, 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. [6] 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 do not mention from which countries hydrogen is imported, in which state (e.g. gaseous, liquified or as liquid ammonia) and at which import costs. In contrast, the German energy agency [7] 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 in gaseous state via pipelines. The scenarios conducted by the Fraunhofer Institute for Solar Energy Systems [8] show a range of 120–330 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 [9] 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 utilized. 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, pathways and costs are not given.

One of the main reasons for the differences in the expected hydrogen demand in the year 2045 is that some applied energy system models [8,9] do not include the non-energetic use of hydrogen for the chemical industry or for the production of steel and therefore potentially underestimate the hydrogen demand in the industrial sector. Prognos et al. [6] expect that chemical products, which are currently produced in Germany using fossil fuels, will be mainly imported in the future. Thus, the potentially needed hydrogen for these products is not included in the German hydrogen demand. Furthermore, some studies [6,7] investigate the energy demand by coupling of simulation models for the demand sectors industry, transport and buildings with an optimization model for the energy supply. Thus, the hydrogen demand in these studies is not an overall cost-optimal solution. Other studies [8,9] analyze the hydrogen demand and supply with integrated energy system models, where the hydrogen utilization is part of the cost-optimal solution. However, the demand sectors are often only modelled with limited detail.

Besides these studies, which share the goal of German greenhouse gas neutrality in the year 2045, other studies analyze the future role of hydrogen in the German energy system. Reuβ et al. [10] examine spatially resolved hydrogen supply chains for Germany, but usage of hydrogen is limited to the transport sector. Similarly, Husarek et al. [11] use an energy system model to analyze hydrogen supply and distribution for the German mobility sector. The potential hydrogen demand for the decarbonization of the German industry is assessed by Neuwirth et al. [12], but they do not state how the needed hydrogen will be supplied. Welder et al. [13] investigate scenarios for hydrogen supply, transport, storage and demand in a future German energy system and show that seasonal hydrogen storage is an integral part of all scenarios. However, they only include the hydrogen demand from the transport and industry sector in their analysis and do not model the entire German energy system in detail. Hydrogen production via electrolysis and hydrogen storage in salt caverns in Germany are analyzed by Michalski et al. [14]. They demonstrate that flexible operation of electrolyzers lowers the curtailment of wind parks and decreases the residual peak load in the power system, but do not model the hydrogen demand at all. Gils et al. [15] show that flexible hydrogen production is central for the integration of volatile renewable energies into the energy system. Yet, their analysis is focused on the role of sector coupling and uses exogenously defined energy demands of the industrial, transport and building sector as input data. Peterssen et al. [16] analyze the influence of photovoltaic potentials and hydrogen import prices on the hydrogen supply in a climate neutral German energy system. However, they do not include all energy demands in their applied energy system model and focus on the supply side. Lux et al. [17] investigate the role of hydrogen in a greenhouse gas-neutral German energy system by the year 2050. They show the importance of geological hydrogen storage and of a European hydrogen transport infrastructure to supply the future hydrogen demand. Yet, they take the future energy demands as input parameters and only optimize the energy supply.

Additionally, several studies analyze the role of hydrogen from a European perspective. Caglayan et al. [18] use an energy system model to examine a European energy system which is entirely based on renewable energy. They design an infrastructure for supply, transport and storage of hydrogen, but do not analyze the usage of hydrogen in detail. Sasanpour et al. [19] examine the role of hydrogen in the European power and transport sector and show that hydrogen remains a key element of the European energy transition even if costs for hydrogen imports and domestic hydrogen production are doubled. Hydrogen supply strategies and sector coupling in the European energy system are analyzed by Frischmuth et al. [20]. They demonstrate that cross-sectoral flexibility decreases the capacity expansion of flexible power plants and that the ratio between hydrogen imports and domestic hydrogen production strongly depends on hydrogen prices. Seck et al. [21] couple three optimization models to analyze the European hydrogen supply and usage. They show that most of the hydrogen is used in the sectors transport and industry, but no results for individual countries are given.

The literature review shows that various papers analyze certain aspects of the role of hydrogen for a future German energy system, but to the best of our knowledge no paper provides an analysis in which supply, storage and usage of hydrogen are modelled and optimized in detail in a single integrated energy system model. While supply, transport and storage of hydrogen have been investigated in detail, hydrogen usage in previous work is often based on exogenous assumptions and not part of the optimization. Studies which analyze the usage of hydrogen focus only on a specific demand sector (e.g. industry or mobility) or model the hydrogen demand with limited detail and thus cannot identify transformation strategies for these demand sectors. Similarly, previous work on the European role of hydrogen often lacks a detailed modelling and analysis of the hydrogen usage. Furthermore, even if results on hydrogen usage in the European energy system are given, they do not contain detailed results on the country level. Studies, which share the goal of a greenhouse gas-neutral German energy system by the year 2045, also lack a detailed modeling of the energy demand sectors or are unable to provide a cost-optimal transformation pathway for the entire German energy system. Therefore, the role of hydrogen in the demand sectors industry, mobility and buildings in a greenhouse gas-neutral Germany remains unclear. Additionally, further research is needed to identify cost-effective use cases for hydrogen applications in these sectors.

This paper helps to close the identified research gap and provides a holistic analysis of the hydrogen usage, supply and storage in a greenhouse gas-neutral Germany by the year 2045. We apply an integrated energy system model which includes all energy demand sectors in detail and the demand for hydrogen as a feedstock. Thus, we are able to show the hydrogen usage in the demand sectors industry, mobility and buildings during the transformation to a greenhouse-gas-neutral Germany. The detailed modelling of these sectors allows us to identify applications for a cost-effective usage of hydrogen for the emission reduction of the German energy system. As the integrated energy system model optimizes supply, storage and usage of energy and feedstocks at the same time, we can provide a consistent transformation pathway for the German energy system. This includes the competition between hydrogen imports and domestic hydrogen production which is part of the optimization problem. Moreover, we investigate the provision of security of supply in periods with low energy supply by wind energy and photovoltaics through long-term hydrogen storage, which is often neglected in existing literature. Additionally, we analyze the optimal operation of electrolyzers in an energy system based on volatile renewable energies. As previous work showed that future hydrogen import costs have a significant influence on the hydrogen supply, we conduct a sensitivity analysis in which we vary the hydrogen import costs in the year 2045 to identify the influence on the German energy system design.

Methodology

The following paragraphs describe the energy system model NESTOR [22], which was chosen for the analyses in this paper. Other energy system models, which can analyze the German energy system and its transformation towards greenhouse gas neutrality, exist, but are not suited to close the identified research gap. These existing German energy system models are briefly discussed in the following:

REMod [23] is an integrated energy system model which analyzes the German energy system in an hourly resolution. However, the demand sectors industry and mobility are not modelled in detail and rely on exogenous assumptions on the development of energy demands and future hydrogen usage. Similarly, the integrated energy system model REMIND [24] lacks a detailed modelling of the demand sectors industry, mobility and buildings. Thus, additional models are needed to identify the development of energy demands in these sectors and no overall cost-optimal transformation pathway can be given. While the European TIMES PanEU [25] energy system model includes all demand sectors in the optimization, the modelling of industry, mobility and buildings is limited in detail. As a result, TIMES PanEU is not able to analyze the usage of hydrogen as a feedstock (e.g. in the chemical industry or steel production) and cannot show a complete analysis of the future role of hydrogen. Thus, the limited modelling of demand sectors in other German energy system models prevents the application of these models for closing the targeted research gap.

In contrast, the energy system model NESTOR depicts the demand sectors industry, mobility and buildings in detail and includes the usage of energy carriers (e.g. hydrogen) as a feedstock in industry. Thus, NESTOR is suited to analyze the usage of hydrogen in a future energy system and show transformation pathways for the demand sectors. Therefore, we use this energy system model to analyze the role of hydrogen in a greenhouse gas-neutral Germany. In the first section we describe characteristics, the objective function and relevant boundary constraints of the NESTOR model. Furthermore, the methodologies for the input data generation, the relevant input data and the scenario design of this paper are presented in the following sections.

Energy system model NESTOR

The analysis in this paper was conducted with the integrated energy system model NESTOR (National Energy System model with SecTOR coupling) [22]. This optimization model depicts the entire German energy system and analyzes cost optimal transformation pathways to greenhouse gas-neutrality. It represents the sectors energy supply, industry, buildings and transport through an hourly resolved network of energy sources, conversion technologies, storages and energy demands. Furthermore, it includes the usage of energy carriers as a feedstock for industrial production processes (e.g., in the chemical industry) [22].

The operation of the energy model is driven by the energy and feedstock demands which must be met in every hour of every optimization year. Hereby, demands are set as useful energy demands (e.g. heated area), demands for production of industrial goods or passenger transport demands. To meet these demands the energy system models contains various detailed modelled process chains for each demand. A detailed description of the modelled process chains in the industrial sector can be found in Kullmann et al. [22], while the modelling of the demand sectors buildings and mobility is shown by Lopion [26]. The decision which technologies and which energy carriers are used to meet the demands is part of the optimization problem. Thus, all technologies of all sectors of the energy system model compete with each other for the cost-minimal solution.

The optimization problem of the energy system model contains the entire network of components and is solved by minimizing the annual system costs. The system costs consist of fixed and variable costs for all components y of the energy system model. Fixed costs are annual investment costs and fixed operational costs. The annual investment costs are calculated with the average specific investment costs $C_{0,y}$ of a component, which are converted to annual costs with the capital recovery factor r_y and multiplied with the installed capacity x_y of the component. The fixed operational costs $m_{fix,y}$ are given as percentage of the investment costs and are multiplied with the specific investment costs $C_{0,y}$ and the installed capacity x_y of the component. The variable costs consist of variable operational costs $m_{var,k}$, the energy flows $\dot{x}_{k,t}$ on every connection k between two components and the length of a time step Δt. These variable costs are summed up over all connections k and time steps t. To account for cost uncertainties and obtain more robust results, the objective function of NESTOR contains a quadratic term. Thereby, the annual fixed costs of a component y are given with a cost range, where s_y is the maximum deviation of the investment costs from the average specific investment costs $C_{0,y}$. This cost range relates to the difference between upper $x_{ub,y}$ and lower bound $x_{lb,y}$ of the installable capacity of a component y. The quadratic annual fixed costs are then summed up over all components y and minimized together with the annual variable costs. A detailed derivation of this quadratic objective function *f(x)* (equation (1)) can be found in Lopion et al. [27].

$$\min f(x) = \min \sum_{y \epsilon Y} \left[C_{0,y} \cdot (1 - s_y) \cdot x_y + \frac{C_{0,y} \cdot s_y}{x_{ub,y} - x_{lb,y}} \cdot x_y^{\,2} \right] \cdot (r_y + m_{fix,y}) + \sum_{k \in K} \sum_{t \in T} m_{var,k} \cdot \dot{x}_{k,t} \Delta t \quad (1)$$

Besides the objective function, several additional boundary constraints must be fulfilled. A major boundary constraint is the limitation of the yearly greenhouse gas emissions of the entire system, which must be less than or equal to the maximum amount of yearly greenhouse gas emissions Ω_{max} (equation (2)). The greenhouse gas emissions of the energy system are calculated with the specific greenhouse gas emissions $\omega_{k,t}$ of an energy flow $\dot{x}_{k,t}$ and the time step size Δt. These emissions are then summed up over all energy flows k and time steps t.

$$\sum_{k \in K} \sum_{t \in T} \omega_{k,t} \dot{x}_{k,t} \Delta t \leq \Omega_{max} \quad (2)$$

To adequately model Germany's pathway to greenhouse gas neutrality, the energy system model accounts for all greenhouse gas emissions from the represented sectors as well as the emissions from agriculture and waste treatment. Furthermore, the model includes technologies to capture CO_2 from point sources or directly from the atmosphere (Direct Air Capture of CO_2) and store it permanently in geological storages in Germany, which can be used to offset residual emissions. Other boundary constraints include the balance of energy flows, storage levels and conversion efficiencies. As an example, the boundary constraint for conversion technologies, which convert incoming energy or material flows to outgoing energy or material flows, is given below in equation (3). Thereby, incoming energy or material flows $\dot{x}_{u,k,t}$ of a conversion technology u multiplied with the conversion efficiency $\eta_{u,k,t}$ must be equal to the outgoing energy or material flows of this component. The equations for other boundary constraints can be found in Lopion [26] and are not repeated in the interest of brevity.

$$\eta_{u,k,t} \cdot \sum_{k \in K_{u,in}} \dot{x}_{u,k,t} = \sum_{k \in K_{u,out}} \dot{x}_{u,k,t} \quad (3)$$

The spatial resolution of the NESTOR model is limited to one single region for the entire German energy system. Thus, the generation of energy is located at the same virtual point as the demand for energy [26]. To incorporate different weather conditions, which influence the electricity generation of wind turbines and photovoltaic plants, Germany is split into nine pseudo-regions for these fluctuating renewable energies. Thus, the spatial differences in electricity generation of these renewable powerplants are taken into account, while keeping the computational effort limited [22,26].

On the temporal side, the resolution of the model is 1 h. Therefore, all energy balances must be met in each hour of an optimization year. To analyze a cost-optimal transformation pathway from the current energy system to a future energy system, a myopic back casting approach is used. First, the energy system is optimized for the target year 2045 by minimizing the system costs. The results of this target year optimization are then used to determine upper and lower bounds for the expansion of technologies for every time step of the transformation pathway. These 5-year time steps are subsequently optimized, starting with the existing energy system in the year 2020 up to the target year 2045. In each of these years the system costs of the energy system are minimized with respect to the spanned upper and lower bounds for the capacity expansion and all other boundary constraints like energy balances and emissions limits. This approach ensures a cost-effective transition from the current energy system towards greenhouse gas neutrality. A detailed description of the myopic back casting approach can be found in Lopion [26].

Methodologies for input data generation

Renewable energy potentials are central input data for the energy system model NESTOR. The potential for the installation of wind turbines and photovoltaic (PV) plants in Germany is determined with the methodology by Risch and Maier et al. [28]. They investigate the potential of onshore wind, offshore wind and open-field photovoltaic with land-eligibility analyses using high-resolution land-use datasets and the open-source tool GLAES [29]. The rooftop photovoltaic potential is calculated using three-dimensional building data [28]. In the next step, the calculated potentials and weather data are used to generate timeseries for the electricity generation of wind turbines and photovoltaic plants. This is done with the open-source tool RESKit [30]. Afterwards, the potentials and generation timeseries are aggregated to the nine pseudo-regions of the energy system model NESTOR. The renewable energy potentials used in this work are given in Table 1.

Hydrogen import potentials and costs are other important input data. Potentials and costs for global hydrogen production and import of liquid hydrogen via ship to Germany are determined with the simulation model InfH2 [32]. It includes the entire value chain for green hydrogen imports from electricity production, electrolysis, liquefaction and ship transport to Germany. To determine hydrogen production potentials, global renewable energy potentials are calculated with GLAES [29] and RESKit [30]. Hydrogen, which is produced with renewable electricity, is then distributed globally with InfH2 [32] by minimizing the system costs. This approach leads to potentials and costs for liquid hydrogen imports to Germany. Costs of green hydrogen imports via pipelines from Southern Europe and North Africa to Germany are estimated with the approach by Brändle et al. [33]. They combine a cost analysis of hydrogen production from renewable energy with a cost analysis of gaseous hydrogen transport via newly built hydrogen pipelines or repurposed natural gas pipelines. The potential for natural gas pipeline reassignment for hydrogen is based on results by Cerniauskas et al. [34]. Afterwards, the import potentials and costs are passed to the NESTOR model, which calculates if it is cheaper to produce green hydrogen in Germany or import it. The hydrogen import costs used in this work are given in Table 2.

Table 1 – Maximum potential for installation of wind turbines and photovoltaic plants in Germany, based on Stolten et al. [31].

	Renewable energy potential in GW
Offshore wind energy	82.2
Onshore wind energy	363.6
Open-field photovoltaic	248.4
Rooftop photovoltaic	454.7

Table 2 – Calculated costs for hydrogen imports to Germany for the years 2030 and 2045.

Import costs in €/MWh	2030	2045
Green H_2 via ship (liquid)	96.6	96.6
Green H_2 via pipeline (gaseous)	92.1	69.5

Table 3 – Key framework data, based on Stolten et al. [31].

Year	2020	2030	2040	2045
Living area in billion m^2	3.590	3.833	3.935	3.984
Passenger transport demand in billion pkm	1122	1121	1118	1117
Freight transport demand in billion tkm	691	776	861	903
Greenhouse gas emission limit in Mt CO_{2eq}	810	438	150	0

Additionally, the integrated energy system model NESTOR uses techno-economic data (e.g., investment costs and efficiencies of technologies) and energy, transport and material demands (e.g., demand for production of industrial goods) as input data. A selection of key framework data like the development of living area in Germany or transport demands is given in Table 3. The development of industrial production is based on continuous growth in gross value added of 1.2% per year. These demands for production of industrial goods are set individually for the modelled process chains and can be found in the appendix of Stolten et al. [31]. Projections for the development of investment costs of technologies are based on an extensive literature research and can also be found in the appendix of Stolten et al. [31] together with the used literature sources.

Scenario design

The central boundary condition for this scenario are the legally binding emission reduction targets from the Federal Climate Change Act [3] (see Table 3), which must be met by the optimization model. This results in a required emission reduction of the German energy system by at least 65% by the year 2030 compared to 1990 levels. Furthermore, the German energy system must be greenhouse gas neutral in year 2045. These emission targets are set as overarching targets for the entire energy system and do not include sector-specific emission goals This is done to ensure a cost-effective emission reduction, where all reduction measures in all sectors of the energy system compete. Besides the reduction targets from the Federal Climate Change Act and the legally stipulated phase-out of nuclear energy [35] and coal power [36], no additional energy transition goals or political limitations must be met by the energy system model. Furthermore, political instruments like subsidies, taxes and CO_2 prices are not included in this scenario. The purpose of this scenario choice is to analyze Germany's transformation towards greenhouse gas neutrality from a system perspective independent from political measures which distort the cost-optimal transformation pathway. Thus, the role of hydrogen and all other results are solely based on the optimization of the German energy system with the energy system model NESTOR with respect to the given boundary constraints. In addition to the cost-optimal transformation pathway in this scenario, a sensitivity analysis is conducted to determine the influence of different hydrogen import costs on the energy system design in the year 2045. Disruptive price shocks, such as the drastic increase of European natural gas prices in the year 2022, are not considered in the analyses, as this paper aims to show the role of hydrogen in the long-term transformation of the German energy system. Further details on the scenario design can be found in the study by Stolten et al. [31], as the scenario design in this paper is closely related to this study.

Results and discussion

This section describes and discusses the results of the optimized scenario. First, overarching scenario results of the transformation of the entire German energy system towards greenhouse gas neutrality are presented (section Transformation of the German energy system). Second, the role of hydrogen in a greenhouse gas neutral energy system is analyzed in detail (section Role of hydrogen in a greenhouse gas neutral Germany). Lastly, the results of the conducted sensitivity analysis on different hydrogen import costs are discussed (section Sensitivity analysis: Hydrogen import costs).

Transformation of the German energy system

To achieve greenhouse gas neutrality in the year 2045, all sectors of the German energy system must almost completely reduce their emissions. All unavoidable emissions in the year 2045 must be offset by negative emissions of the same amount to reach net zero greenhouse gas emissions. Fig. 1 shows the development of the German greenhouse emissions from the year 2020 to the target year 2045. In the optimized year 2020 about 810 Mt CO_{2eq} are emitted in Germany. Thereby, the largest emissions stem from the energy sector with about 36% (about 291 Mt CO_{2eq}) of the total greenhouse gas emissions. By the year 2030 the total emissions are reduced to 438 Mt CO_{2eq} (−65% compared to the year 1990). The energy sector shows the fastest decarbonization and decreases its emissions by about 80% compared to the year 2020. This emission reduction is achieved by a fast expansion of renewable energy sources and an accelerated phase-out of coal, so that no electricity in the year 2030 is produced by coal or lignite power plants. Consequently, the electricity generation in the year 2030 is based to more than 90% on renewable energy, which enables a coupling of the energy sector with the other sectors of the energy system. In contrast, the emissions of the sectors industry and transport decrease only by about 20% from 2020 to 2030.

In the year 2045 the sectors energy, buildings and transport are nearly greenhouse gas neutral. However, in total about 90 Mt CO_{2eq} residual emissions are remaining and must be offset by negative emissions. Most of the remaining emissions stem from agriculture (about 48 Mt CO_{2eq}) and unavoidable process emissions in the industry sector (about 35 Mt CO_{2eq}). Through usage of carbon capture and storage technologies, remaining emissions in the cement industry are reduced by about 13 Mt CO_{2eq}. Nevertheless, about 77 Mt CO_{2eq} negative emissions are needed. With about 57 Mt CO_2 most of the negative emissions are accounted for by capturing CO_2 directly from the atmosphere and storing it permanently in geological storages. The usage of biomass in powerplants and industrial furnaces which are equipped with carbon capture technologies accounts for another 20 Mt CO_2 of negative emissions. In total, about 90 Mt of CO_2 must be permanently stored in the year 2045. Suitable geological storage locations for CO_2 are depleted natural gas fields or saline aquifers, where CO_2 is stored in pores of reservoir rock formations. Most of these suitable storage locations are located in the northern parts of Germany and below the German parts of the North Sea. In total the technical geological storage potential for CO_2 in Germany is about 12 billion t CO_2 [37] and therefore sufficiently large for the necessary storage of 90 Mt of CO_2 in the year 2045 and following years. The costs for transporting CO_2 to the storage locations and permanently storing it range from about 15 €/tCO_2 to about 28 €/tCO_2 [38,39], depending on transport distance and storage location. However, our optimization shows that costs for capturing CO_2 directly from the atmosphere are around 215 €/tCO_2 in the year 2045 and thus significantly larger than costs for CO_2 transport and storage. Despite these high costs for negative emissions, capturing CO_2 from the atmosphere and storing it permanently in geological storages is necessary for achieving greenhouse gas neutrality.

The needed emission reduction causes a transformation of the currently fossil fuel-based German energy system to a renewable energy-based system. This transition is shown by the development of the primary energy consumption in Fig. 2. The German primary energy consumption decreases from about 3591 TWh in the year 2020 to about 2164 TWh in the year 2045 (−40%). While today's primary energy consumption is

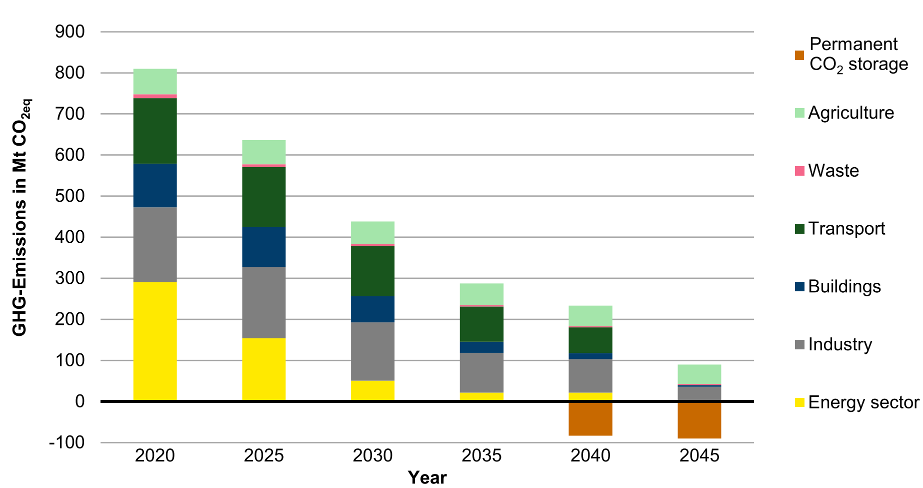

Fig. 1 – Development of German greenhouse gas emissions (GHG) in the transformation towards greenhouse gas neutrality in the year 2045, based on study by Stolten et al. [31].

based to about 85% on fossil fuels, the German energy supply is defossilized in the course of the transformation. The consumption of lignite and coal decreases until the year 2030 through the phase-out of coal powerplants. After the year 2030 blast furnaces using coal for steel production are replaced by direct reduction processes using hydrogen. Usage of mineral oil and natural gas accounts for the majority of the primary energy consumption in the year 2030 but is subsequently reduced fast. In the building sector oil and natural gas boilers are replaced by heat pumps, while buildings are refurbished to reduce the heat demand of the building stock. In the transport sector gasoline and diesel vehicles are replaced by battery electric vehicles or vehicles using fuel cells.

In the year 2045 renewable energy carriers supply almost the entire energy demand. The majority is supplied by wind turbines (about 710 TWh), photovoltaic plants (about 470 TWh) and bio energy (about 428 TWh). The remaining mineral oil (about 91 TWh) is used as a feedstock in the chemical industry. Furthermore, hydrogen (about 196 TWh), electricity (about 72 TWh) and synthetic kerosene (about 111 TWh as Power-to-liquid imports) are imported to Germany. These imports are significantly lower than today's fossil fuel imports, which results in a decrease of the import rate from about 74% [40] in the year 2019 to about 22% in the year 2045. Thus, the greenhouse gas neutral energy system is significantly less dependent on energy imports.

Role of hydrogen in a greenhouse gas neutral Germany

Fig. 3 shows that hydrogen plays a pivotal role for the German energy transition and the transformation to greenhouse gas neutrality. In the year 2030, 104 TWh (about 3.1 Mt) of hydrogen are used in the German energy system. With about 48 TWh the highest hydrogen demand stems from the industry sector, followed by the transport sector with about 30 TWh of hydrogen demand in the year 2030.

The hydrogen demand increases to about 412 TWh (about 12 Mt) by the year 2045. Thereby, the industry sector is with 267 TWh the main consumer of hydrogen. Furthermore, about 117 TWh hydrogen are used in the transport sector in the year 2045. In the power sector, about 24 TWh of hydrogen are used in hydrogen gas turbines to produce electricity. These hydrogen gas turbines are only run to bridge periods with little electricity generation from wind turbines and photovoltaic plants. Hydrogen usage in the building sector in the year 2045 is not significant, as heat pumps dominate the heat supply.

Throughout the transformation the industry sector dominates the hydrogen demand and thus the industrial hydrogen demand is analyzed in detail (see left side of Fig. 4). In the year 2030, 48 TWh of hydrogen are needed. With 33 TWh the majority of this demand is grey hydrogen, which is produced decentral via methane steam reforming and is mostly used in the chemical industry.

The hydrogen demand in the industrial sector increases to 267 TWh in the year 2045. In the cement industry about 38 TWh of hydrogen are used for supplying process heat. About 87 TWh of hydrogen are used in the steel industry to produce iron via direct reduction of iron ore. Additionally, steel is produced from recycled steel scrap in electric furnaces, which results in an almost emission-free steel production in the year 2045. Furthermore, about 20 TWh of hydrogen are used to produce ammonia via the Haber-Bosch process. The main demand of hydrogen in the year 2045 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.

In the transport sector (see right side of Fig. 4) the hydrogen demand is majorly used for heavy trucks with fuel cells. Of the 117 TWh of hydrogen in the year 2045, about 63% (73 TWh) are used in these trucks, which dominate the freight transport on roads. About 32 TWh of hydrogen are used in cars and light duty vehicles in the year 2045. However, fuel cell cars only account for 30% of the passenger transport demand, as battery electric vehicles dominate the individual mobility.

To meet this hydrogen demand, both domestic hydrogen production via electrolysis and green hydrogen imports are needed. The development of the German hydrogen supply is shown in Fig. 5. In the year 2030 about 29 TWh of hydrogen are produced domestically via electrolysis. For this purpose, an electrolyzer capacity of 15 GW_{H2} is needed. In addition to the

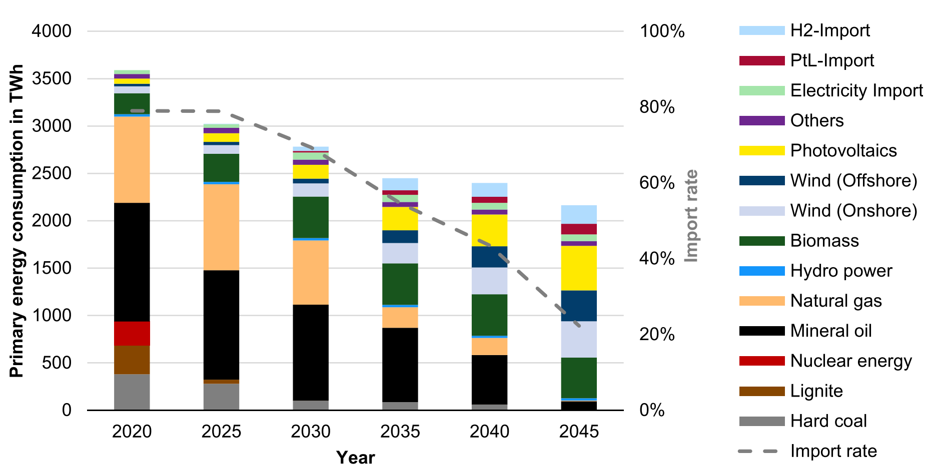

Fig. 2 – Development of primary energy consumption and energy import rate in the transformation towards greenhouse gas neutrality, based on study by Stolten et al. [31].

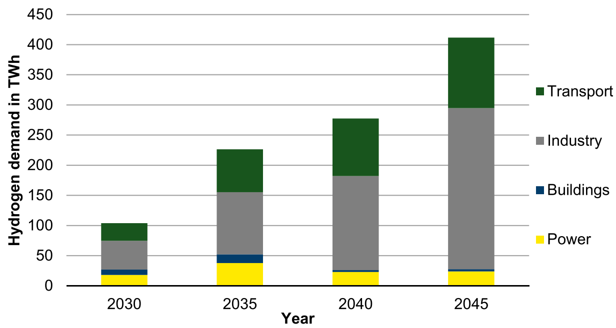

Fig. 3 – Development of hydrogen demand by sector in the transformation to greenhouse gas neutrality, based on study by Stolten et al. [31].

grey hydrogen production in the industry, about 45 TWh of green hydrogen are imported to Germany.

In the year 2045 about 47% of hydrogen is imported from other European countries or Northern Africa via pipelines or ships. With 150 TWh most of the hydrogen is imported via pipelines from Southern Europe (mostly Spain) or Northern Africa (mostly Algeria) using mainly reassigned natural gas pipelines. The average import costs via pipeline from these regions are 2.3 €/kg_{H2} in the year 2045. In this paper, the import potential via pipelines from Southern Europe and Northern Africa is limited to 150 TWh in total. This is mainly due to bottlenecks in the existing pipeline network, as capacity expansion of European pipelines is not part of this analysis. Thus, additionally 46 TWh of hydrogen are imported in liquid state via ships from Northern Europe. The average import costs for hydrogen from the United Kingdom (about 23 TWh), Ireland (about 14 TWh) and Norway (about 9 TWh) are 3.2 €/kg_{H2}. The cost difference between these import routes is mainly caused by the assumption that hydrogen from Northern Europe must be liquefied, transported by ship and then regasified in German harbors. An analysis of hydrogen imports from Northern Europe to Germany via pipeline is not part of this scenario but would probably result in lower hydrogen import costs.

With about 219 TWh, more hydrogen is domestically produced via electrolysis than imported to Germany. Therefore, 71 GW_{H2} electrolyzer capacity are needed in the year 2045 (see Table 4). This results in about 311 TWh electricity demand for domestic hydrogen production, which accounts for more than 25% of the total electricity demand in the year 2045 (about 1216 TWh). To supply this demand a strong expansion of wind turbines and photovoltaic plants is necessary. The installed capacity of onshore and offshore wind turbines increases from about 62 GW in the year 2020 to about 285 GW in the year 2045. Likewise, the installed capacity of open-field and rooftop photovoltaic plants increases from about 51 GW in the year 2020 to 449 GW in the year 2045. While the potentials for this capacity expansion exist in Germany, a significant acceleration of today's expansion rates are necessary to reach this cost-optimal renewable energy capacities. The expansion rate for wind turbines must increase from on average about 3.3 GW per year between 2012 and 2021 [41] to about 8.9 GW per year, whereas the expansion rate of photovoltaic plants must increase from on overage about 2.5 GW [41] per year to about 15.8 GW per year.

Hydrogen gas turbines and long-term hydrogen storage are key elements for securing the electricity supply in a renewable-based energy system. They are especially important during dark lulls, which describe periods with little energy generation from wind and solar power. In this paper we make sure that even in extreme situations like dark lulls the energy supply is secured. Thus, we take a dark lull of two weeks in January into account, where only 10% of the capacity of wind energy turbines and photovoltaic plants is available for electricity generation. To overcome this period, controllable power plants like hydrogen gas turbines or biomass power plants are used for meeting the electricity demand. In

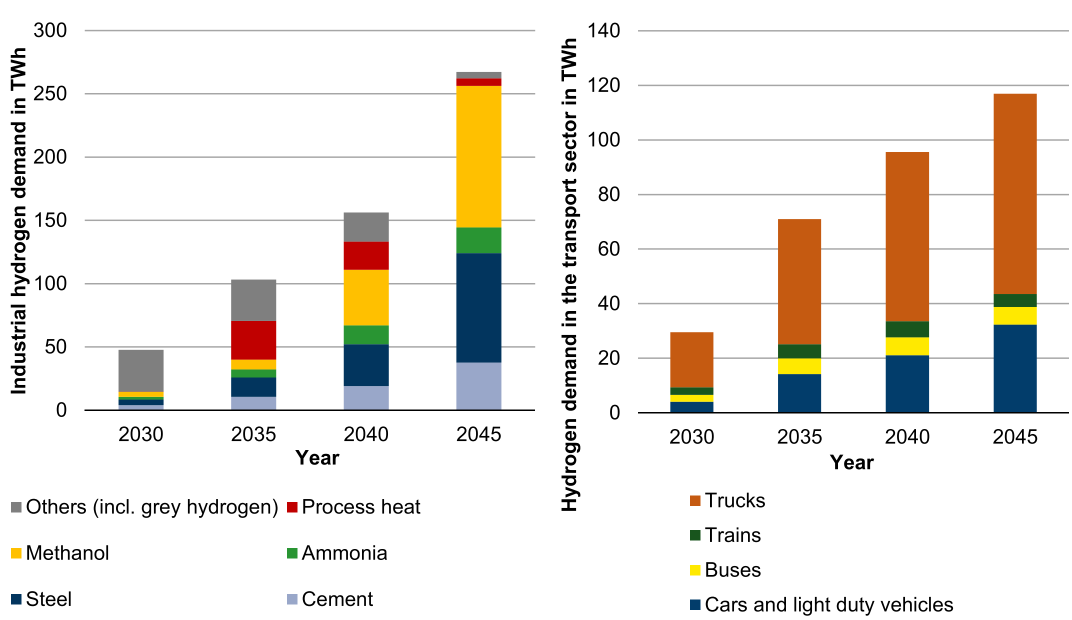

Fig. 4 – Development of hydrogen demands in the industry (left) and transport sector (right) by use, based on study by Stolten et al. [31].

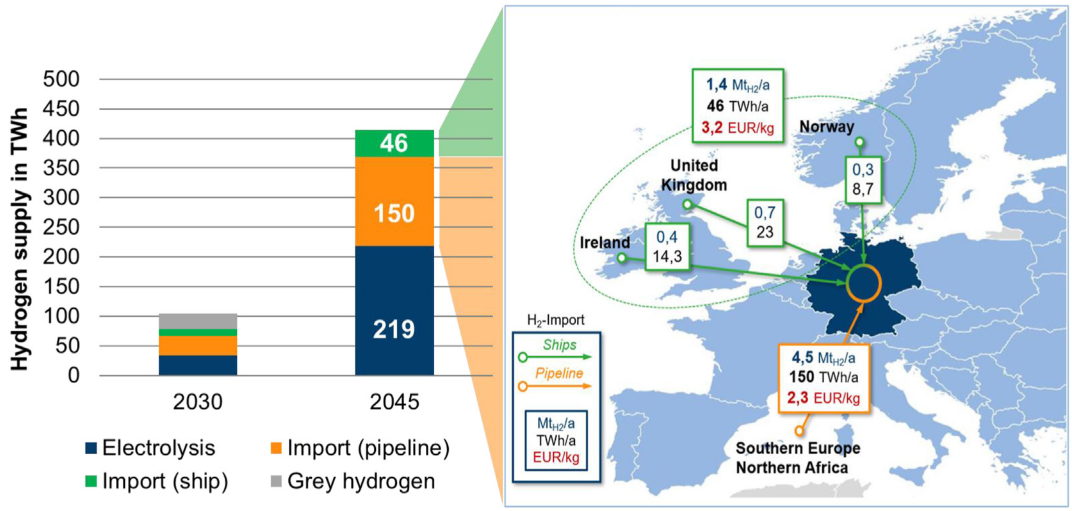

Fig. 5 – Development of the German hydrogen supply via domestic electrolysis and imports via pipelines and ships to Germany (left) and hydrogen import routes and costs in the year 2045 (right), based on study by Stolten et al. [31].

the year 2045 about 54 GW of biomass power plants and about 32 GW of hydrogen gas turbines are installed, which are run on almost full capacity during the dark lull. Thus, on average 72 GWh electricity per hour are generated through these controllable powerplants during these two weeks in January (see Fig. 6). The hydrogen for the operation of hydrogen gas turbines is extracted from long-term hydrogen storages. Additionally, during the dark lull most of the hydrogen demand in the sectors industry and transport is taken from these hydrogen storages, as no hydrogen is produced domestically in this period. Therefore, in total about 35.4 TWh of long-term hydrogen storage capacity is needed to supply hydrogen during this period and balance 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.

Fig. 6 shows the variation of the hydrogen storage level throughout the year 2045. The hydrogen storages are filled during summer and are emptied during the winter months, especially during the dark lull in January. Furthermore, it is shown that electricity generation from wind turbines and photovoltaic varies throughout the year but accounts for most of the electricity supply. Nevertheless, controllable powerplants and storages are needed during timeframes with little electricity generation from wind energy and photovoltaics.

Fig. 7 shows this variation in the hourly electricity generation exemplary for September 2045. The daily generation profile of photovoltaic (PV) plants is clearly visible, but also the large differences in electricity generation of wind turbines. This leads to large fluctuations of electricity generation from these renewable energy sources in September 2045. During periods with little electricity generation from PV and wind turbines, hydrogen turbines, biomass power plants and electricity storages supply the needed electricity. Thus, an installed electricity storage capacity of about 562 GWh is needed in the year 2045. These storages are charged during daytime and discharged during nighttime.

Another key source of flexibility for the energy system are the installed electrolyzers. They adjust their hydrogen production based on the available electricity and thereby help to balance the electricity generation and demand. Fig. 7 shows that electrolyzers are shut down, when not enough electricity is produced from PV and wind turbines. In turn, electrolyzers are run with full capacity during times with high electricity generation through renewable sources. In September 2045 the operation of electrolyzers is mainly determined by the generation profile of PV plants but electricity generation of wind turbines also influences the operation strategy.

This operation strategy of electrolyzers helps to balance the intermittent nature of renewable energies and results in about 3100 full load hours in the year 2045. As electrolyzers with polymer electrolyte membranes are well suited for part-load operation and cold start-up [42], they are chosen as electrolyzers for this operation strategy. Overall, the flexible operation of electrolyzers, heat pumps and other sector

Table 4 – Electrolyzer capacity and electricity demand for electrolysis in the years 2030 and 2045 together with electricity consumption of the entire energy system and expansion of wind energy and photovoltaic.

Year	2030	2045
Installed electrolyzer capacity	15 GW_{H2}	71 GW_{H2}
Electricity demand for domestic electrolysis	45 TWh	311 TWh
Total electricity consumption	562 TWh	1216 TWh
Installed capacity of wind turbines (onshore and offshore)	102 GW	285 GW
Installed capacity of photovoltaic plants (open-field and rooftop)	150 GW	449 GW

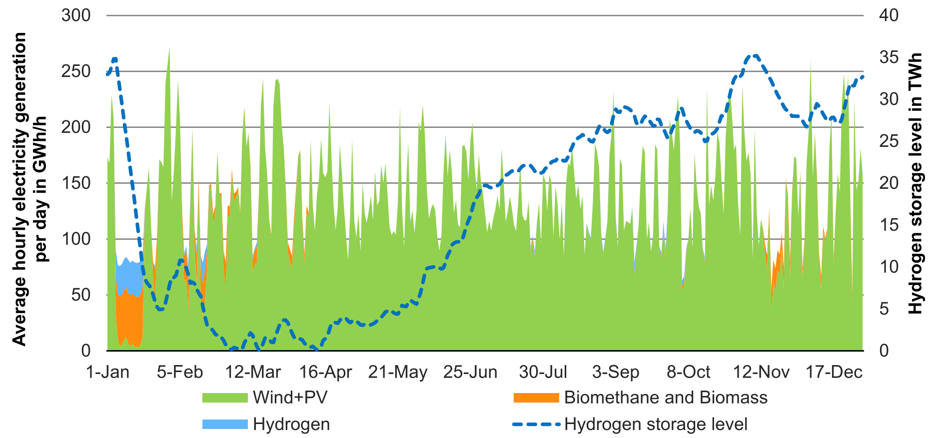

Fig. 6 – Electricity generation and storage level of hydrogen storages in course of the year 2045. For representational reasons the hourly electricity generation is shown as an average per day. Based on study by Stolten et al. [31].

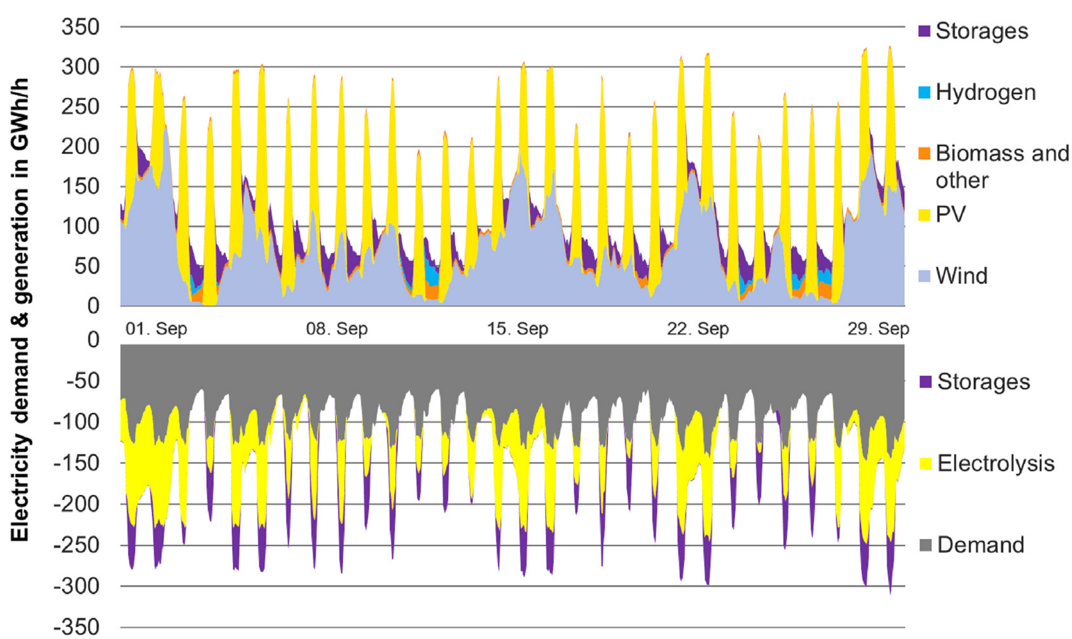

Fig. 7 – Hourly electricity generation and demand in September of the year 2045.

coupling processes is a key element for an energy system based on volatile renewable energy sources.

Sensitivity analysis: hydrogen import costs

To analyze the influence of different hydrogen import costs on the future energy system, this sensitivity analysis varies the import costs for hydrogen in the year 2045. In the optimistic case, hydrogen import costs are uniformly set to 2.2 €/kg_{H2} for all import routes. In the pessimistic case, it is assumed that there is no timely ramp-up of the European hydrogen economy. Thus, hydrogen import costs are uniformly set to 4.2 €/kg_{H2}.

Fig. 8 shows that the optimistic case for future hydrogen import costs leads to an increase in hydrogen demand to about 603 TWh in the year 2045. This increase is mainly due to the use of hydrogen for process heat generation in the industrial sector. With lower hydrogen import costs it is cost-efficient to replace biomass in the process heat generation and use hydrogen instead. The biomass is instead used for electricity generation and for providing negative emissions.

Additionally, more hydrogen is used in the power sector to supply hydrogen gas turbines. In contrast, the pessimistic case results in only a slight decrease of the hydrogen demand to 379 TWh in the year 2045. The hydrogen demand in the sectors industry and transport remains constant compared to the base case. However, in the pessimistic case no hydrogen is used in the power sector. Thus, no hydrogen gas turbines are installed and biomass powerplants must bridge dark lulls on their own.

Parallel to the increase in hydrogen demand in the optimistic case, the import share also increases to 84% due to the cost advantage of hydrogen imports compared to domestic hydrogen production. In this case, about 507 TWh of hydrogen

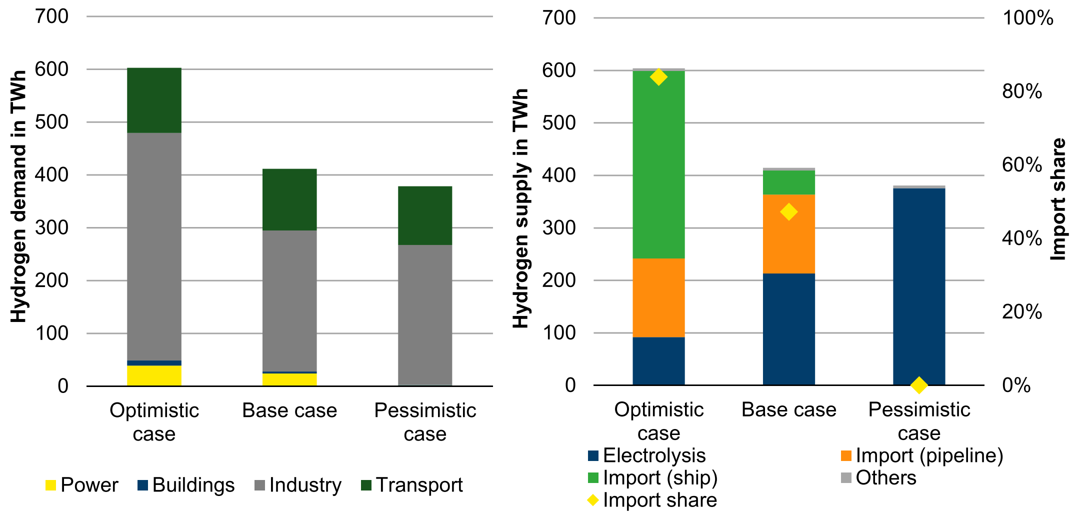

Fig. 8 – Hydrogen demand (left) and supply (right) in the year 2045 with variation of hydrogen import costs, based on study by Stolten et al. [31].

are imported (see Fig. 8), which results in an increase of about 311 TWh compared to the base case. The additionally required hydrogen is imported within Europe by ships from Northern Europe to Germany, since no further increase of pipeline imports was assumed. As only about 92 TWh of hydrogen are produced domestically via electrolysis, the installed electrolyzer capacity decreases to 37 GW_{H2} (see Table 5). Consequently, the electricity consumption and installed capacity of wind turbines and PV plants decreases in this optimistic case.

In the pessimistic case for future hydrogen import costs, no hydrogen is imported to Germany, as domestic hydrogen production via electrolysis is more cost effective (see Fig. 8). This leads to an increase of the installed electrolyzer capacity to 111 GW_{H2} and an electricity consumption of about 1457 TWh in the year 2045 (see Table 5). To supply this electricity demand, about 152 GW of additional wind turbines and PV plants compared to the base case are needed. Thus, in the year 2045 about 529 GW of photovoltaic plants (open-field and rooftop) and about 357 GW of wind turbines (onshore and offshore) are installed. The potentials for this capacity expansion exist in Germany, but the expansion rate for these renewable energy sources must increase once more compared to the base case. Therefore, a complete waiver of hydrogen imports and full domestic hydrogen supply is possible but leads to additional challenges regarding the capacity expansion of electrolyzers and renewable energy sources.

Conclusions

This paper demonstrates that hydrogen is an essential aspect of Germany's transition to greenhouse gas neutrality by the year 2045. The cost-optimal transformation pathway shows that in the year 2030 about 104 TWh of hydrogen are used in the German energy system. This demand increases to about 412 TWh in the year 2045 whereof most is used in the industry and transport sector. Particularly, the use of hydrogen in the chemical industry and in steel production is essential as there are no cost-effective alternatives for the emission reduction required for achieving greenhouse gas neutrality. Furthermore, the results of the conducted sensitivity analysis show that higher hydrogen import costs do not decrease the hydrogen demand in the industry and transport sector significantly. Thus, the usage of hydrogen in these sectors is robust and a central measure for emission reduction.

Our analysis shows that both domestic hydrogen production via electrolysis and hydrogen imports are equally important for the German hydrogen supply. Despite the import of about 196 TWh of hydrogen in the year 2045, the import rate of primary energy decreases from 74% in the year 2019 to about 22%. Furthermore, the diversified hydrogen supply chains increase the geostrategic security of supply for Germany.

Table 5 – Influence of different hydrogen import costs on the greenhouse gas-neutral energy system in the year 2045.

Year 2045	Optimistic case for hydrogen import costs	Base case	Pessimistic case for hydrogen import costs
Hydrogen import costs	2.2 €/kg (uniformly)	3.2 €/kg (ship) 2.3 €/kg (pipeline)	4.2 €/kg (uniformly)
Hydrogen demand	603 TWh	412 TWh	379 TWh
Domestically installed electrolyzer capacity	37 GW_{H2}	71 GW_{H2}	111 GW_{H2}
Hydrogen import share	84%	47%	0%
Total electricity consumption	1004 TWh	1216 TWh	1457 TWh
Installed capacity of wind turbines and PV plants	576 GW	734 GW	886 GW
Difference in total system costs compared to the base case	- 7.2%	0	+1.1%

The imports via pipelines from Southern Europe and North Africa dominate the hydrogen import, as they are cheaper than importing hydrogen via ships. Due to bottlenecks in the existing pipeline network, liquid hydrogen imports from Northern Europe are also needed. A capacity expansion of the pipeline network is not investigated in this paper but could lead to a replacement of liquid hydrogen imports with more imports via pipelines.

The domestic supply of more than half of the demanded hydrogen is cost-effective and requires about 71 GW_{H2} installed electrolyzer capacity in the year 2045. Thereby, the electricity demand for electrolysis of about 311 TWh accounts for a quarter of the total German electricity demand in the year 2045. To meet this electricity demand, a large expansion of installed wind turbines and photovoltaic plants is essential. The sensitivity analysis shows that in case of higher import prices, it is cost-effective to supply the entire German hydrogen demand via domestic electrolysis. However, this would require an even faster expansion of the capacities of renewable energy sources.

Furthermore, hydrogen is a key element for securing the energy supply in a renewable energy-based energy system. Hydrogen gas turbines are used to bridge dark lulls with little electricity generation by wind turbines and PV plants. To supply the needed hydrogen during dark lulls, long-term hydrogen storage in salt caverns is crucial. Filling these hydrogen storages during summer and emptying them during winter helps to balance the seasonal variation of renewable energy sources.

Our analysis shows that a flexible operation of electrolyzers is pivotal in a greenhouse gas neutral energy system based on renewable energies. The electrolyzers are shut down during periods with little electricity generation through wind turbines and PV plants and are in turn run on full capacity during times with high renewable electricity generation. Thus, they help to balance the intermittent nature of renewable energies. From a system perspective, this flexible operation is cost-optimal and should be encouraged.

The conducted sensitivity analysis shows that costs for hydrogen imports to Germany have a significant influence on the greenhouse gas-neutral energy system. Besides a resulting import share range from 0% to 84%, varying the hydrogen import costs has a significant influence on the expansion of electrolyzers, wind turbines and photovoltaic plants. Furthermore, the sensitivity analysis shows that a full domestic hydrogen supply is possible but leads to additional challenges regarding the capacity expansion of electrolyzers and renewable energy sources.

To reduce the uncertainty regarding hydrogen import costs, future work should include a detailed analysis of all possible import routes and costs. As imports via existing pipelines are generally more cost-effective than imports via ship in liquid state, a detailed investigation of pipeline imports from Northern Europe to Germany should be included. Furthermore, the possibility of expanding the existing pipeline network should be considered. While the analyses in this paper are limited to the German energy system, the interdependence between Germany and other European countries deserves complementary attention. Inclusion of other European countries in the modeling approach, could lead to different optimization results regarding hydrogen import routes and the required expansion of renewable energy sources, hydrogen turbines and long-term hydrogen storages. Furthermore, a detailed modelling of the European energy system with its demand sectors would allow to analyze the future role of hydrogen in Europe in detail.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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