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# Implications of hydrogen import prices for the German energy system in a model-comparison experiment

Richard Schmitz [a,*], Julian Brandes [b], Hannah Nolte [b], Christoph Kost [b], Benjamin Lux [c], Michael Haendel [c], Anne Held [c]

[a] Fraunhofer Institute for Energy Economics and Energy System Technology IEE, Joseph-Beuys-Straße 8, 34117, Kassel, Germany
[b] Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110, Freiburg im Breisgau, Germany
[c] Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Str. 48, 76139, Karlsruhe, Germany

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ABSTRACT

With its ability to store and transport energy without releasing greenhouse gases, hydrogen is considered an important driver for the decarbonisation of energy systems. As future hydrogen import prices from global markets are subject to large uncertainties, it is unclear what impact different hydrogen and derivative import prices will have on the future German energy system. To answer that research question, this paper explores the impact of three different import price scenarios for hydrogen and its derivatives on the German energy system in a climate-neutral setting for Europe in 2045 using three different energy system models. The analysis shows that the quantities of electricity generated as well as the installed capacities for electricity generation and electrolysis increase as the hydrogen import price rises. However, the resulting differences between the import price scenarios vary across the models. The results further indicate that domestic German (and European) hydrogen production is often cost-efficient.

## 1. Introduction

The use of hydrogen and its derivatives is an important component for implementing a successful energy transition in Germany and Europe. However, the question for which applications hydrogen use makes sense and to what extent is currently subject of debate. Against this backdrop, the German government introduced the National Hydrogen Strategy (NHS) in June 2020 for the first time, providing a framework for the future production, transportation, and utilization of hydrogen and its derivatives in Germany [1]. In the summer of 2023, the NHS was updated and extended considering changing developments, including the Ukraine conflict [2]. According to the coalition agreement of the German government, the planned ramp-up of electrolysis capacity was doubled from its original 5 GW–10 GW by 2030 [3]. In addition, infrastructure expansion must be planned and accelerated. Germany aims to establish itself as a lead market for hydrogen technologies by 2030. Another significant aspect of the ramp-up of hydrogen and its derivatives relates to the question of a suitable import strategy. However, both the quantities to be imported and the required prices for hydrogen and its derivatives are still unclear. Since there is currently no global liquid hydrogen market and trade, this leads to the question how the German and European energy systems react to different hydrogen import prices. To answer this research question, this paper aims to provide first insights by applying three different energy system models with three different underlying approaches and focus topics.

There is existing literature on hydrogen import prices and on the import prices' influence on the European or respective national energy system, see Section 2. Furthermore, there are different tools for the calculation of hydrogen import prices. However, to the authors' best knowledge, no existing literature analyses the impact of different hydrogen import prices with more than one energy system model.

The remainder of this paper is structured as follows. Section 2 presents the current state of the literature on hydrogen import prices, tools for the calculation of those import prices, and the import prices' influence on the European or respective national energy system. Section 3 then introduces the conceptual approach of the analysis as well as the three energy system models REMod, Enertile and SCOPE Scenario Development (SCOPE SD). Afterwards, Section 4 describes the case study approach with its nine different model runs and the used general

* Corresponding author.
*E-mail addresses:* richard.schmitz@iee.fraunhofer.de (R. Schmitz), julian.brandes@ise.fraunhofer.de (J. Brandes), hannah.nolte@ise.fraunhofer.de (H. Nolte), christoph.kost@ise.fraunhofer.de (C. Kost), benjamin.lux@isi.fraunhofer.de (B. Lux), michael.haendel@isi.fraunhofer.de (M. Haendel), anne.held@isi.fraunhofer.de (A. Held).

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**Abbreviations**

| | |
|---|---|
| AEL | Alkaline electrolysis |
| BEV | Battery Electric Vehicle |
| CAPEX | Capital expenditures |
| CCS | Carbon capture and storage |
| CHP | Combined heat and power |
| CMA-ES | Covariance Matrix Adaptation Evolutionary Strategy |
| COP | Coefficient of Performance |
| DAC | Direct Air Capture |
| DACCS | Direct Air Carbon Capture and Storage |
| ETS | (European Union) Emissions Trading System |
| GHG | Greenhouse gas |
| HVDC | High-voltage direct-current transmission |
| LP | Linear programming |
| MENA | Middle East and North Africa |
| NHS | National Hydrogen Strategy |
| OPEX | Operational expenditures |
| PEMEL | Polymer Electrolyte Membrane electrolysis |
| PHEV | Plug-in Hybrid Electric Vehicle |
| PtG | Power-to-Gas |
| PtL | Power-to-Liquid |
| PtX | Power-to-X |
| PV | Photovoltaics |
| REEV | Range Extended Electric Vehicle |
| SCOPE SD | SCOPE Scenario Development |
| SMR | Steam methane reforming |
| SOEL | Solid Oxide electrolysis |

scenario assumptions, import prices for hydrogen and renewable fuels, and further techno-economic assumptions. The results for the German energy system are then shown and discussed in Section 5, followed by Section 6, which draws relevant conclusions.

## 2. Literature review

This section looks at previous work divided into the following three categories: Different tools for the calculation of hydrogen import prices, literature on hydrogen import prices, and the import prices' influence on the European or respective national energy system.

A recently published example of the former is Fraunhofer IEE's "Power-to-X atlas" which contains a broad assessment of global production and export sites. The tool itself can be used in [4], while a detailed description containing further information on the import options of Power-to-X (PtX) products to Europe and on the production potential of PtX fuels for all countries outside of Europe can be found in [5]. Another calculation tool for hydrogen import prices is the "Cost tool for the calculation of global production and supply costs of green hydrogen and hydrogen-based synthetic fuels" from the Institute of Energy Economics at the University of Cologne [6]. It allows to calculate the potential future production costs of green hydrogen and hydrogen-based synthetic fuels for 113 countries and the respective transportation cost to Germany [7]. The "PTX Business Opportunity Analyser" from Agora Energiewende and Öko-Institut e.V. focuses on the competitive edge of different countries with regard to the delivered cost of PtX molecules in the year 2050 [8], whereas the hydrogen tool from the company "acatech" is only suitable for the year 2030 [9].

When determining hydrogen costs and prices, it can be distinguished between domestic European production and imports from outside of Europe [10]. The recently published study in [11] analyses the production costs of hydrogen in twelve selected countries, but only for the year 2030. Regarding imported hydrogen to Europe in 2050, many different price forecasts have been published in recent years. A meta-analysis of 30 studies in [12] compares the supply costs of chemical energy carriers and concludes that the mentioned forecasts diverge by up to a factor of 5. Similar to that, supply costs for importing hydrogen to Germany of 4.2–11 ct/kWh$_{th}$ are gathered in [13], which correspond to the equivalent of 42–110 EUR/MWh$_{th}$. The study in [14], calculating a cost optimised climate-neutral energy system in Germany, uses varying hydrogen import prices from 1.25 EUR/kg to 5 EUR/kg, which is the equivalent of a range of 37.5 EUR/MWh$_{th}$ to 150 EUR/MWh$_{th}$. The projected import costs for Germany in [15] are a little lower, mentioning 1.0 to 1.3 EUR/kg, roughly corresponding to a range of 30–40 EUR/MWh$_{th}$. In [16] it is assumed that for Germany and Finland, imported green hydrogen will be more expensive than domestically produced hydrogen.

When analysing the transport costs of hydrogen, many studies compare transport by ship on the one hand and transport by pipeline on the other. As an alternative, a detailed analysis of hydrogen transportation infrastructures using ammonia and methanol as hydrogen carriers can be found in [17]. In addition, there are publications that address hydrogen production costs in specific regions of the world. For example, Publication [18] deals with hydrogen production costs in the Middle East and North Africa (MENA) region in the years 2030 and 2050, while publication [19] deduces these production costs in Australia. In general, it is formulated in [20] that hydrogen production will predominantly occur in regions that have lower electricity costs than other regions.

It is widely accepted that a fully decarbonised European power system can benefit from hydrogen [21]. As stated in [22], hydrogen will be primarily used in the industry and transport sectors. Using the SCOPE SD model which is also part of this publication's analysis [23], calculates two price sensitivities (79 EUR/MWh$_{th}$ and 94 EUR/MWh$_{th}$) for the European energy system with green hydrogen imports from outside of Europe. Publication [24] focuses on the impact of different renewable fuel import price scenarios (72.50/85.00/97.50 EUR/MWh$_{th}$) on the use of hydropower in the European energy system. It analyses European electricity generation volumes and capacities, domestic hydrogen production, and water values of European hydropower assets. An example of a country-specific analysis on the use of hydrogen in a national energy system is [25] with its decarbonisation pathway for Norway.

In the literature are many different scenarios for the German energy system, which is the focus of this publication. A corresponding review of these scenarios can be found in [26] determining economic benefits of hydrogen and synthetic carriers for Germany based on 37 scenarios. The study in [27] has a high practical relevance, as it is used to support the German hydrogen strategy development by examining the use of hydrogen in the German energy system. A recent transformation pathway of the German energy system can be found in [28] in which the integrated energy system model "NESTOR" is used to analyse the role of hydrogen in achieving greenhouse gas (GHG) neutrality.

As already stated in the introduction, there is no literature source that analyses the impact of different hydrogen import prices with more than one energy system model. This means that potential inaccuracies of the models themselves are ignored, although these inaccuracies can strongly influence the results of the respective studies. The energy system models used in this paper have been established in many practical studies, see [29] for the Enertile model in particular and sections 3.2, 3.3, 3.4 for all of the models, and have, besides other research or consulting purposes, already participated in other model comparison experiments. The models SCOPE SD and REMod, together with the "TIMES-PanEU" model, have been compared within the "RegMex" project [30] with respect to the electricity, heat, and transport sectors as well as the accompanying sector coupling. As part of the "MOD-EX-POLINS" project [31], the SCOPE SD model has recently been further compared with the "DIMENSION", "EMMA", "Joint Market Model" and "PowerFlex" models with respect to carbon pricing [32], coal phase-outs [33], and combined heat and power systems [34].

To address the mentioned knowledge gap, this work analyses the impact of different import prices for hydrogen and its derivatives on the German energy system by comparing the results of three different energy system models. This will answer the research question what range the electricity generation volumes, installed capacities for electricity generation, and installed capacities for electrolysis exhibit.

## 3. Methodology

After outlining the conceptual approach for the underlying analysis in section 3.1, this chapter introduces the energy system models REMod (section 3.2), Enertile (section 3.3), and SCOPE SD (section 3.4).

### 3.1. Conceptual approach

To answer the research question, this work analyses three hydrogen import price scenarios, i.e. low, medium, and high (see section 4.2), executed by the three energy system models REMod, Enertile and SCOPE SD. To that end, the case study performs nine individual model runs (see section 5). The models are exposed to the same set of scenarios at essential points (see section 4). The results of the case study for the German energy system especially focus on electricity generation volumes, renewable electricity production capacities, domestic electrolyser capacities, and hydrogen imports from non-European and European countries. The goal of this analysis is to give the models as much freedom as possible in their optimisation, so that the different strengths of the models (detailed modelling of the German transformation pathway in REMod vs. integration of Germany in the European energy system in SCOPE SD and Enertile) can be used and shown.

To explore the implications of different import price pathways, we apply three energy system models with different methodological focuses. Due to the heterogeneity of the models used, our result ranges are more robust than the application of one energy system model, where results strongly depend on the strengths and weaknesses of the applied model. First, we use SCOPE SD, which analyses the European energy system with a detailed consideration of the electricity market mechanisms in potential combination with the electricity grids. Second, we apply the energy system model Enertile with hourly and spatially resolved modelling (10 × 10 km) of the electricity sector and the renewable energy potentials. Third, we rely on the national energy system model REMod with a focus on cross-sectoral system development and the modelling of pathways towards a target year. Further details describing the three energy system models can be found in Table 1.

Their main differences concern the optimisation of power plant dispatch, the transformation pathway until 2045, the spatial resolution and the weather years: While SCOPE SD and Enertile optimise the hourly dispatch of all power plants, storage technologies, and consumers, REMod calculates a simplified power plant dispatch based on the merit order after performing an optimisation of the power plant capacities. While REMod as a pathway optimisation model shows the development of the energy system until 2045 for each individual year, SCOPE SD and Enertile only optimise the scenario year 2045 itself. In turn, however, REMod optimises only the geographical area of Germany, whereas SCOPE SD and Enertile include 28–33 countries across continental Europe and the British Isles. Enertile uses 2010 as the underlying weather year, while SCOPE SD uses the weather year 2012 because it is well-suited to represent extreme weather conditions and their implications for design choices by the modelling framework as it features a two-week "Kalte Dunkelflaute" period (cold dark doldrums) [35]. To represent the effects of different weather years, REMod uses the weather years 2011–2015 in rotation for each simulation year until 2045.

**Table 1**
Overview of the applied energy system models, table design based on [32,36].

| | Enertile | REMod | SCOPE SD |
|---|---|---|---|
| **Model type** | Bottom-up model for European long-term low-carbon energy system scenarios | Combined evolutionary optimisation and simulation of the energy system | Bottom-up techno-economic partial equilibrium model for European long-term low-carbon energy system scenarios |
| **Programming language** | Java | Julia | MATLAB |
| **Optimisation algorithm** | Barrier (interior point) algorithm | Covariance Matrix Adaption – Evolutionary Algorithm | Barrier (interior point) algorithm |
| **Foresight** | Perfect foresight | Perfect foresight for yearly optimisation; limited foresight for hourly simulation | Perfect foresight |
| **Sector coupling** | Combined optimisation of electricity, heat (heat pumps and heat grids), and hydrogen production to cover sectoral energy demands from industry, tertiary, residential, and transport. | Technology sharp optimisation of industry, heat, transport, and energy economy | Optimisation of the power system and all relevant bi- and multivalent technology combinations at the sectoral interfaces with the building, industry, and transport sectors |
| **Optimisation of** | | | |
| dispatch | Yes | No, but simulation | Yes |
| investment | Yes | Yes | Yes |
| decommissioning | No | Yes | No |
| **Programming of** | | | |
| Pathway optimisation | No | Yes | No |
| Rolling horizon | No | No | No |
| Binary variables | No | No | No |
| **Spatial resolution** | 33 European countries in 25 model regions | 10 regions for Germany | 28 European countries |
| **Time resolution** | Hourly simulation of a scenario year | Hourly simulation from today to 2050 | Hourly simulation of a scenario year |
| **Weather year** | 2010 | 2011–2015 | 2012 |

### 3.2. Modelling the transformation pathway of the German energy system with REMod

REMod combines simulation and optimisation approaches by using optimisation for the investment/capacity planning and simulation for the hourly dispatch. The used optimisation algorithm is the Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES) which belongs to the class of evolutionary algorithms. During each iteration, many possible optimisation vectors are simulated, and the best values become parents to the optimisation vectors in the next iteration. In the simulation, the expansion of all technologies in Germany is estimated on a yearly basis. The simulation runs on an hourly basis for every year until 2050 with the optimised transformation path. The model can be parameterised for multiple regions - in this analysis, ten regions for Germany are used. There are about 90 technologies considered and optimised, including all relevant technologies for energy production (i.e., wind power, solar photovoltaics (PV), gas- and hydrogen-turbines), conversion (electrolysers and power-to-liquid systems), storage (stationary and mobile batteries, hydrogen storage, central and decentralised heating storage), transmission lines (hydrogen and electricity), demand technologies as well as the imports of electricity and synthetic fuels. It should be noted that upper and lower boundaries are implemented for the calculation of German electricity imports and exports, as there is no detailed modelling of the neighbouring countries. For the calculation of the demand, the technology mix of the building, industry, and transport (private and commercial) sectors is estimated by the optimisation. Consequently, the expansion of each sector is optimised in interaction with all the other sectors. Therefore, the expansion of each technology can influence the expansion of all other technologies in the transition of the energy system. As the optimisation always receives the impact of the optimised expansion on the system costs of the complete transformation path, the optimisation predicts a transformation path. Relevant publications using REMod can be found in Refs. [37,38], a schematic overview of basic technologies considered in REMod is shown in Fig. 1.

### 3.3. Modelling the European energy system in 2045 with Enertile

Enertile is a bottom-up model designed to optimise large, coupled energy systems. The model covers the interlinked supply of electricity, heat, and hydrogen. The objective of the model is to minimise the costs of converting, transporting, and storing these energy vectors up to the year 2050. In a linear programming (LP) approach, the optimisation covers both capacity expansions and dispatch of relevant infrastructures. Fig. 2 shows the model coverage and interactions of individual subsystems of the modelled energy supply system.

Enertile has a high temporal and spatial resolution. In this study, it covers the simulation year 2045 for 8760 h using perfect foresight. Electricity generation potentials for renewable technologies are calculated using real weather data on a grid of edge length 6.5 km for Europe. The cost minimisation of the European energy supply system aggregates

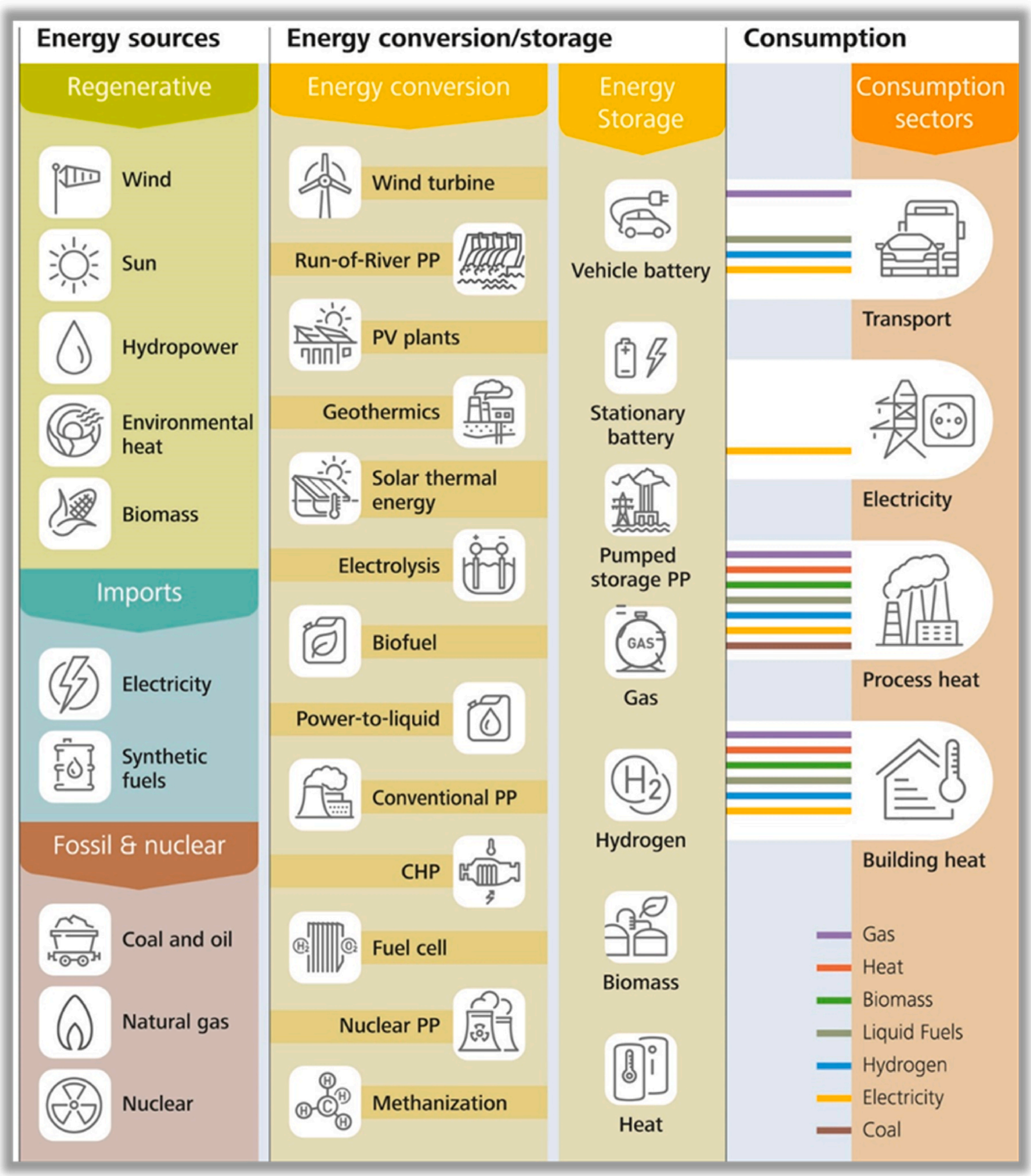


**Fig. 1.** Schematic overview of basic technologies considered in REMod, own illustration.

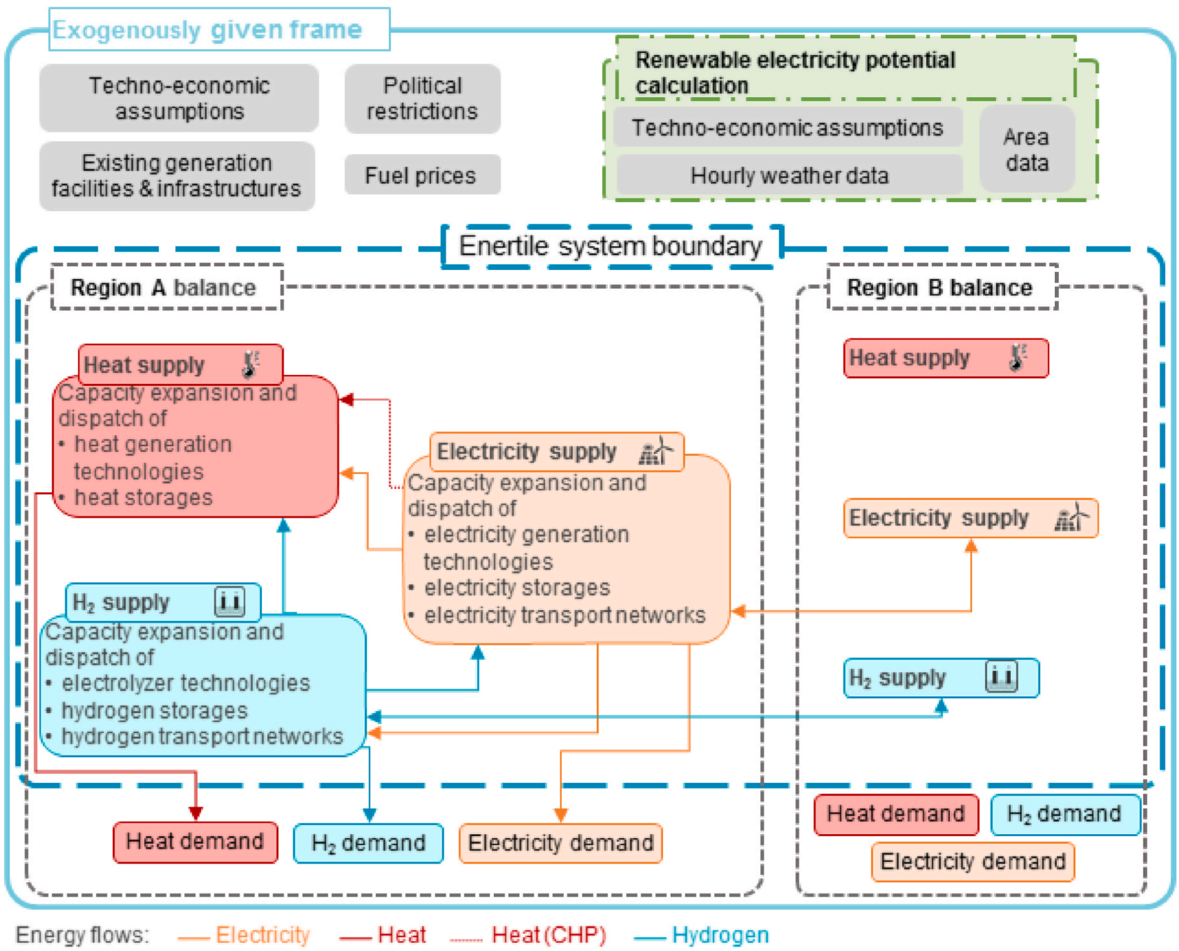


**Fig. 2.** Schematic overview of the modelled energy supply system in Enertile, own illustration as already shown in [27].

these renewable electricity generation potentials mainly on a country level. Germany has a higher spatial resolution than other European countries with a subdivision into seven zones.

For hydrogen production in Enertile, electrolytic hydrogen generation in a model region competes, on the one hand, with other, partly flexible electricity demand applications for cheap hours of renewable electricity generation and, on the other hand, with hydrogen imports. These hydrogen imports are possible either by considering the expansion and deployment of the required renewable power generation technologies, electrolysis, and hydrogen transport services in other European model regions or via representative price series from non-European countries.

More detailed descriptions, including mathematical formulations and recent applications of Enertile in case studies, can be found in Refs.

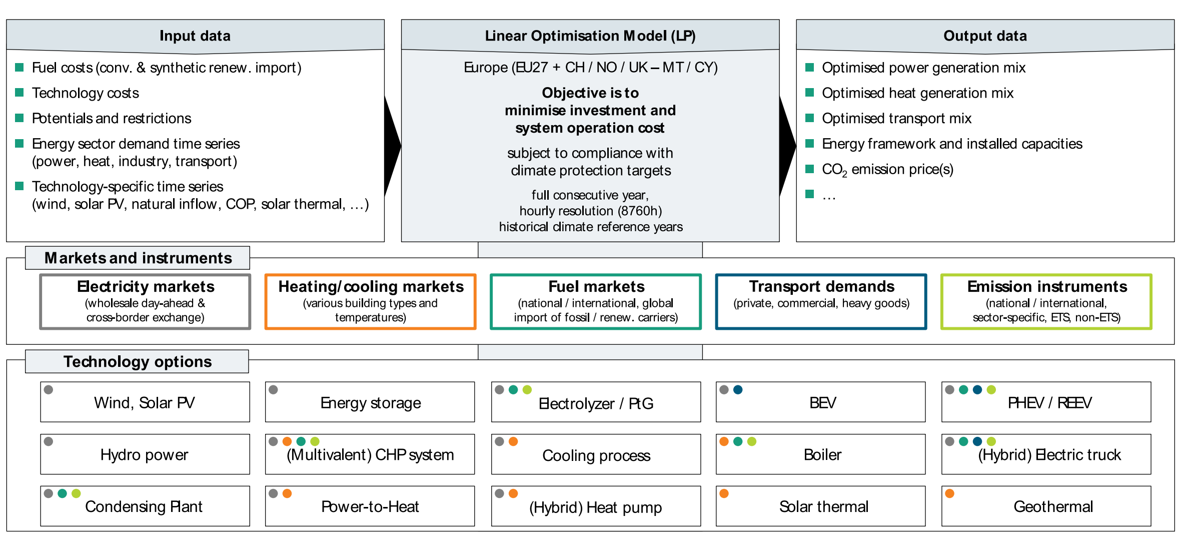


**Fig. 3.** Schematic overview of the pan-European cross-sectoral capacity expansion planning framework SCOPE SD, own illustration as already shown in [24].

[27,39–43].

### 3.4. Modelling the European energy system in 2045 with SCOPE SD

The pan-European cross-sectoral capacity expansion planning framework SCOPE SD is a bottom-up techno-economic partial equilibrium model. Recent mathematical formulations and applications of SCOPE SD can be found in Refs. [23,24,44–47]. Fig. 3 illustrates the structure, components, and typical in- and output data of SCOPE SD (upper section) including the interactions of technology options (lower section) in the corresponding markets or policy instruments (middle section). Note that the different dot colours of the technology options indicate the (multi-fold) participation of technology options in the corresponding markets or policy instruments.

The modelling and optimisation framework develops coherent long-term low-carbon energy system scenarios for Europe for a given target scenario year in the future. As shown in Fig. 3, the term "Europe" refers to the 27 member states of the European Union, Switzerland, Norway, and Great Britain, without the islands of Malta and Cyprus. By minimising the generation, storage, and cross-sectoral consumer technology investment and system operation cost, this large-scale LP approach has representations for the traditional power system as well as for all relevant bi- and multivalent technology combinations at the sectoral interfaces with the building, industry, and transport sectors.

Each market area, e.g. every European country, is represented by one node. All units (generation, storage, and cross-sectoral demand technology options), their most important parameters (costs, potentials, and operational characteristics), and their relevant interactions with each other are modelled in hourly resolution. By explicitly modelling national and pan-European fuel markets, it is possible to distinguish between the use of fossil fuels, on the one hand, and synthetic renewables, on the other hand, which are either imported from outside of Europe or produced domestically. To account for climate-neutrality in future scenarios, national and international GHG emission budgets are implemented as a driving force behind investments in low-carbon technologies.

## 4. Scenario description

This chapter begins with an overview of general scenario assumptions in section 4.1. A derivation of import costs for hydrogen and its derivatives from global markets in section 4.2 is then followed by a listing of the most relevant techno-economic assumptions for the analysis in section 4.3.

### 4.1. General scenario assumptions

Considering a GHG reduction of 95% in the scenario year 2045 compared to the year 1990 and taking into account unavoidable emissions, it is assumed that the modelled energy sectors in Germany and Europe become climate-neutral. The energy system models therefore do not allow net GHG emissions in the considered power, transport, building, and industry sectors. While there is no sufficiency in the energy sector, a moderate increase in energy efficiency is assumed for electricity consumers as well as for the building, industry, and transport sectors. In the transport sector, extensive electrification is assumed. Industrial consumption of electricity and other fuels is based on data from Fraunhofer ISI's "FORECAST" model [48].

There is no limit for the import of renewable fuels, e.g. hydrogen, renewable liquid fuels and renewable methane, from outside of Europe. Investments in nuclear energy are not allowed in the models, nor are there any technologies for carbon capture and storage (CCS). Germany's coal phase-out is assumed to be completed by the year 2038. Please note that for offshore wind power, a lower limit of 40 GW in Germany in 2045 was implemented in SCOPE SD and Enertile as the legal setting at 70 GW in 2045 [49] did not take effect until after the modelling was completed.

### 4.2. Deriving import costs and prices for low carbon hydrogen and its derivatives

At present, there is no global hydrogen market with an established pricing mechanism. Instead, hydrogen pricing is predominantly based on bilateral contracts on a local or regional level. For this reason, this chapter estimates future hydrogen prices based on cost calculations for hydrogen production and transport. This means that the estimation rather presents the lower bound of a possible price range, as market-components are missing. Real prices may therefore diverge from this estimation. In addition, different hydrogen production technologies and a wide range of possible techno-economic assumptions already imply a large spread of possible cost ranges. In this analysis, three price scenarios are chosen which are based on the use of blue and green hydrogen using different techno-economic assumptions as shown in Table 2. We realise calculations for three points in time, namely 2020, 2030 and 2050, and use linear interpolation for the years in between.

#### 4.2.1. Low price scenario - based on optimistic assumptions on blue hydrogen

This scenario aims at answering the question how the energy system behaves at comparatively low import prices for hydrogen and its derivatives. The cost calculation assumes the use of blue hydrogen generated by a steam methane reforming (SMR) process with CCS. The relevant cost components of blue hydrogen considered here include the costs for the reformer, fuel costs for natural gas as well as the CCS costs based on [50]. In addition, the share of the GHG emissions including $CO_2$ that cannot be captured is considered.

Further cost components are related to production and transport of natural gas and include $CO_2$ equivalents of methane slip and further $CO_2$ emissions from the upstream process based on [51]. The $CO_2$-equivalents that cannot be abated are assumed to be compensated with an Emissions Trading System (ETS)-price of 160 EUR/t of $CO_2$-equivalent

**Table 2**
Techno-economic parameters used for the estimation of hydrogen import prices, own assumptions based on [4,50–53].

| | General | Steam reformer | Onshore wind | Solar PV | Electrolyser |
|---|---|---|---|---|---|
| **Capital expenditures (CAPEX) in EUR/kW** | – | 955 | 886 | 321 | 470 |
| **Operational expenditures (OPEX) in % of CAPEX** | – | | 4 | 2.5 | 5 |
| **Lifetime in yr** | – | 15 | 22 | 25 | 20 |
| **Full-load hours** | – | 8000 | 4480 | 1700 | 3200–6000 |
| **Efficiency in %** | – | – | – | – | 65 |
| **Fuel costs natural gas in EUR/MWh** | 26–78 | – | – | – | – |
| **CCS costs incl. transport and storage in EUR/$t_{CO2}$** | 35 | – | – | – | – |
| **Direct Air Capture (DAC) in EUR/$t_{CO2}$** | 130–200 | – | – | – | – |
| **Transport and storage costs for negative emissions in EUR/$t_{CO2}$** | 15 | – | – | – | – |
| **ETS-price in EUR/$t_{CO2}$** | 160 | – | – | – | – |
| **Hydrogen infrastructure in EUR/$t_{CO2}$** | 8–20 | – | – | – | – |

by 2030 and later on to be removed from the atmosphere with direct air carbon capture and storage (DACCS) [52]. The corridor determined in the calculations is shown as the blue area in Fig. 4. For the low price scenario in the energy system models, the use of the lower bound is chosen (blue dotted line). There is a slight increase in the lower bound due to slightly increasing gas prices and higher costs for the growing hydrogen infrastructure.

#### 4.2.2. Medium price scenario - based on a mix of blue and green hydrogen

The medium price scenario builds on a mix of blue and green hydrogen. Thereby, the lower bound of green hydrogen costs is assumed to set the price in the beginning of the modelling period, assuming that the CCS-technology has barely been used. Later (around 2030) we assume 60% of the hydrogen to be blue hydrogen and 40% to be green hydrogen, assuming that CCS becomes commercially available. This leads to the assumed price reduction shown in Fig. 4. After 2030, the share of green hydrogen increases, but with significant lower cost reductions. Towards the end of the modelling horizon in 2050, the prices are assumed to reflect the lower bound of green hydrogen production and transport costs. For the medium price scenario in the energy system models, the prices indicated by the grey dotted line in Fig. 4 are chosen.

#### 4.2.3. High price scenario - based on green hydrogen

For the high price scenario, hydrogen is assumed to be completely based on electrolysis using solar PV or onshore wind electricity in the MENA-region. One core motivation for choosing a green hydrogen scenario is the potential lack of political acceptance for the import of green hydrogen. Cost estimations for renewable electricity do not correspond to the “best” generation site in terms of full-load hours for wind and solar PV, but to rather average local weather conditions with large potential export volumes for hydrogen and its derivatives. Thereby, two exemplary cases are calculated, one based on onshore wind and the other one based on solar PV in combination with battery storage. The full-load hours assumed for the renewable energy technologies are based on calculations of the global power-to-x atlas [4]. Different capital costs are used to reflect country-specific risk considerations. Furthermore, different transport options for hydrogen are assumed, namely pipeline transport and ship-based transport of liquefied hydrogen. Hydrogen infrastructure costs are based on [53]. For the high price scenario in the energy system models, the prices indicated by the green dotted line in Fig. 4 are chosen.

Import prices assumed for hydrogen derivatives are then based on the described hydrogen scenarios and adjusted taking the production costs of PtX-products as calculated by [54]. The final import prices used in the energy system models are shown in Table 3.

### 4.3. Further techno-economic assumptions

For further modelling, especially for the transformation pathway development of the energy system with the REMod model, not only the import prices for renewable fuels are important, but also the assumed prices for conventional fuels. These are listed in Table 4.

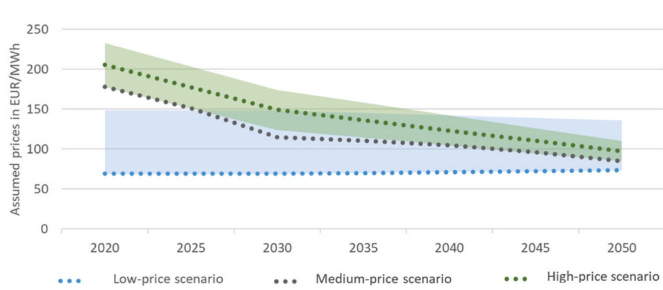


**Fig. 4.** Assumed import prices for hydrogen from non-European countries in EUR/MWh based on own calculations.

All three energy system models can invest in electrolysers for the domestic production of hydrogen. It is distinguished between different types of electrolysers, namely Polymer Electrolyte Membrane electrolysis (PEMEL), Alkaline electrolysis (AEL), and Solid Oxide electrolysis (SOEL). Their respective efficiencies, depreciation periods, stack lifetimes, investment costs, and fixed operating costs are shown in Table 5. For the years between 2015, 2030, and 2050 in REMod, the respective values are linearly interpolated. Please note that Enertile uses all three technologies separately, while REMod averages these technologies and SCOPE SD only uses AEL.

The investment costs of onshore wind plants, offshore wind plants, free field PV, rooftop PV, battery storages, and heat pumps as well as their respective fixed operating costs are harmonised in all three models. Furthermore, the power grid costs for connecting offshore wind plants with sea cables, for connecting onshore wind plants to medium-voltage grids, for high-voltage direct-current transmission (HVDC), and for distribution grids (especially for the expansion of solar PV) are set to the same values in all models.

The interest rate for any investment is set at 6%. The $CO_2$ price is 200 $EUR_{2018}/t_{CO2}$ in 2030 and 1000 $EUR_{2018}/t_{CO2}$ in 2050, in the years in between the price is linearly interpolated.

## 5. Results and discussion

This chapter begins with an analysis of the German energy system’s pathway results towards the year 2045 generated by the REMod model in section 5.1. Afterwards, section 5.2 shows the modelling results of the German energy system for the year 2045 generated by the energy system models REMod, SCOPE SD, and Enertile with a focus on electricity generation volumes, renewable electricity production capacities, domestic electrolyser capacities, and hydrogen imports from non-European and European countries. At the end, section 5.3 compares further effects in different sectors on the German energy system.

Note that the case study result data for the German energy system are available in an open-access repository at https://doi.org/10.5281/zenodo.8307808 [56].

### 5.1. Results for the transformation pathway of the German energy system

The transformation pathway modelled by REMod demonstrates intersectoral dependencies on the way to climate neutrality until 2045. As shown in Fig. 5 with its installed capacities of renewable energy technologies, the different import prices of hydrogen do not have an effect until the year 2030 because according to the assumptions, hydrogen can only be imported from this year on. Thus, the installed capacities of wind power and solar PV are nearly the same in all scenarios until 2030 and only differ after 2030.

As hydrogen can be imported at low prices in the scenario “REMod low”, a total of only 413 GW of wind power and solar PV is installed to reach climate neutrality in 2045. Therefore, more hydrogen is imported and used in the demand sectors. This even results in a decrease of the capacities of onshore and offshore wind power. With increasing prices of hydrogen, the installed capacities of wind power and solar PV also increase. Consequently, the scenario “REMod med” installs a total of 507 GW and the scenario “REMod high” a total of 584 GW of wind power and solar PV. As free field PV and offshore wind power do not strongly differ within the scenarios, the differences mainly occur in onshore wind power and rooftop PV.

As shown in Fig. 6 with its imports of hydrogen and renewable fuels, the scenario “REMod low” with a total sum of 863 TWh in 2045 imports 150 TWh more hydrogen and renewable fuels than the scenario “REMod med”. The scenario “REMod high” imports 240 TWh less than “REMod low” in 2045. In 2045, there is a decrease in hydrogen imports, but this is offset by a large increase in renewable fuel imports.

The results of Figs. 5 and 6 underline that the assumptions for the import prices of hydrogen and its derivatives have a significant impact

**Table 3**
Overview of renewable fuel import prices in $EUR_{2018}/MWh_{th}$, own assumptions.

| | | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| **Scenario "low"** | **Renewable liquid fuels** | 108.4 | 108.4 | 108.4 | 109.2 | 110.1 | 111.0 | 111.9 |
| | **Renewable methane (gaseous import)** | 92.4 | 92.4 | 92.4 | 93.1 | 93.9 | 94.7 | 95.4 |
| | **Hydrogen** | 69.0 | 69.0 | 69.0 | 69.8 | 70.7 | 71.6 | 72.5 |
| **Scenario "med"** | **Renewable liquid fuels** | 217.4 | 190.4 | 132.9 | 132.7 | 136.3 | 132.3 | 124.4 |
| | **Renewable methane (gaseous import)** | 187.4 | 163.9 | 113.7 | 113.6 | 116.7 | 113.2 | 106.3 |
| | **Hydrogen** | 178.0 | 151.0 | 93.5 | 93.3 | 96.9 | 92.9 | 85.0 |
| **Scenario "high"** | **Renewable liquid fuels** | 244.9 | 216.7 | 188.4 | 175.5 | 162.7 | 149.8 | 136.9 |
| | **Renewable methane (gaseous import)** | 242.5 | 214.3 | 186.0 | 173.1 | 160.3 | 147.4 | 134.5 |
| | **Hydrogen** | 205.5 | 177.3 | 149.0 | 136.1 | 123.3 | 110.4 | 97.5 |

**Table 4**
Overview of fossil fuel prices in $EUR_{2018}/MWh_{th}$ in all scenarios, based on the sustainable development scenario of the World Energy Outlook 2019 [55].

| | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| **Hard coal** | 8.1 | 6.8 | 6.8 | 6.9 | 7.0 | 7.0 | 7.1 |
| **Lignite** | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 |
| **Natural gas** | 22.2 | 25.2 | 25.6 | 25.9 | 26.3 | 26.6 | 27.0 |
| **Oil** | 29.8 | 32.3 | 31.8 | 31.3 | 30.8 | 30.2 | 29.7 |
| **Uranium** | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| **Diesel** | 55.4 | 59.1 | 54.2 | 49.9 | 46.1 | 42.8 | 39.9 |
| **Gasoline** | 56.7 | 60.4 | 55.5 | 51.2 | 47.4 | 44.0 | 41.1 |

**Table 5**
Main parameters of domestic electrolyser technologies in all scenarios.

| Technology | Parameter | Unit | 2015 | 2030 | 2050 |
|---|---|---|---|---|---|
| **PEMEL** | Efficiency | % | 57 | 65 | 71 |
| | Depreciation period | yr | 20 | 25 | 27 |
| | Stack lifetime | h | 40,000 | 60,000 | 135,000 |
| | Investment costs | EUR/kW | 1750 | 650 | 400 |
| | Fixed operating costs | EUR/kW/yr | 13 | 8 | 7 |
| **AEL** | Efficiency | % | 63 | 67 | 71 |
| | Depreciation period | yr | 25 | 25 | 30 |
| | Stack lifetime | h | 90,000 | 120,000 | 120,000 |
| | Investment costs | EUR/kW | 1150 | 500 | 375 |
| | Fixed operating costs | EUR/kW/yr | 24 | 24 | 24 |
| **SOEL** | Efficiency | % | 68 | 72 | 72 |
| | Depreciation period | yr | 10 | 20 | 20 |
| | Stack lifetime | h | 11,000 | 45,000 | 90,000 |
| | Investment costs | EUR/kW | – | 800 | 550 |
| | Fixed operating costs | EUR/kW/yr | 32 | 12 | 8 |

on the overall amount of energy carriers that is imported in a cost optimised pathway as well as on the necessary installed capacities of wind power and solar PV. In addition to imports, REMod also increases the electrolyser capacities as well as the capacities of methanation and Power-to-Liquid (PtL) technologies. These resulting expansions are shown in Fig. 7. Note that the electrolyser capacities included in the methanation process and the electrolyser and methanation capacities included in the PtL technologies are not plotted in their respective categories.

In both scenarios "REMod low" and "REMod med", the installed capacity of electrolysers in 2045 is about 10 GW. The installed capacity of electrolysers only changes significantly in the scenario "REMod high" where it reaches more than 25 GW in 2045. As already mentioned, there is no relevant difference between the scenarios before the year 2030.

As the installed capacities of wind power and solar PV change between the scenarios, the hydrogen import price also influences the amount of flexibility that is necessary to stabilize the system, as shown in Fig. 8 with its installed capacities of different storage technologies.

The use of pumped storage power plants is almost identical in all scenarios. In the "REMod low" scenario, only 8 GWh of stationary batteries are installed by 2045. Nevertheless, about 50 GWh are installed by 2030 as import of hydrogen is only possible in the years from 2030 to 2045. The scenario "REMod med" needs 26 GWh of stationary batteries, while the scenario "REMod high" needs about 70 GWh. The term "Mobile Batteries" refers to batteries in electric vehicles that allow vehicle-to-grid flexible charging. In all scenarios, private cars are highly electrified and about 10% of private car users are assumed to provide their cars for flexible charging. This way, the expansion of mobile batteries reaches about 350 GWh.

### 5.2. Main results for the German energy system in 2045

The case study setup investigates three different import price scenarios for hydrogen and its derivatives in three different energy system models. As already pointed out in [24], the main effects result from different investment decisions in the respective system configurations and affect the electricity, industry, building, and transport sectors. For the sake of comparability between the models, the following analyses will be focused on Germany. Please recall that all scenarios imply climate-neutrality for Europe and Germany which means that carbon dioxide emissions are zero from a net position perspective.

To substantiate the impact of different hydrogen import prices on the German electricity system and markets, Fig. 9 first shows the optimised (net) electricity generation balances in Germany in 2045 for each energy system model and each scenario. Here and in the following graphs, the first row shows the results of REMod, the second row shows the results of SCOPE SD, and the third row shows the results of Enertile. From left to right, the columns show the import price scenarios "low", "med", and "high" for hydrogen and its derivatives.

The electricity production in all scenarios and energy system models primarily comes from renewable sources, including onshore and offshore wind, solar PV, hydropower, and burning of hydrogen in centralised power plants. Between the different scenarios, REMod shows the largest differences in the electricity balance, while the results in SCOPE SD and Enertile change only moderately. In general, the amount of electricity produced in Germany increases when the price of hydrogen is higher, mostly because increased domestic hydrogen production via electrolysers leads to an increased demand for electricity. Moreover, electric power becomes a relatively more valuable commodity when electricity generated by burning imported hydrogen becomes more expensive. The hydrogen import price in scenario "low" leads to higher electricity production in central power plants, although the total amount is still small in relation to other energy sources. In all energy system models, most of the electricity production comes from wind energy. In comparison, the scenarios in REMod show the highest electricity production from solar PV, while the scenarios in Enertile show the highest electricity production from burning hydrogen.

Particularly in the case of wind and solar PV, the differences in the amounts of electricity generated result from the installed capacities in each import price scenario and vice versa. The capacities are shown in Fig. 10. A distinction is made between onshore wind and offshore wind

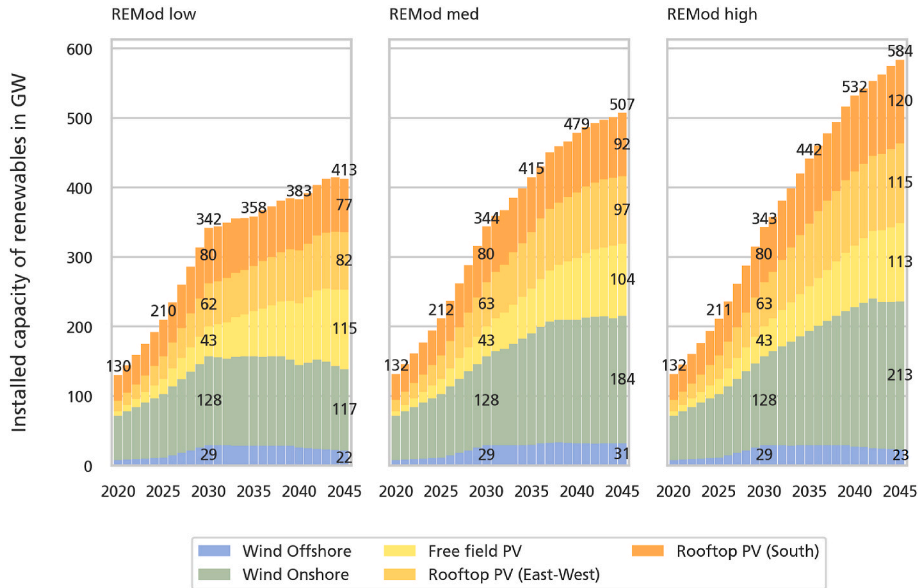


**Fig. 5.** Transformation pathway of installed capacities of renewable energy technologies in Germany in GW, own illustration.

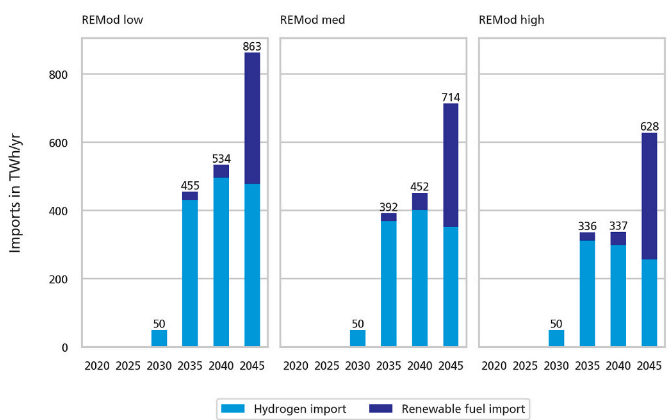


**Fig. 6.** Transformation pathway of imports of hydrogen and renewable fuels to Germany in TWh/yr, own illustration.

as well as between free field PV and rooftop PV.

REMod shows the largest differences between the import price scenarios in terms of installed capacities and the highest capacities overall. In the total sum of capacities, there is almost no difference between scenario “med” and scenario “high” for SCOPE SD and Enertile except for 2 GW of solar PV in SCOPE SD. Offshore wind capacity in REMod increases from 20 GW to 36 GW when imported hydrogen becomes more expensive, while the capacities in SCOPE SD and Enertile do not exceed the implemented lower bound of 40 GW as offshore wind is a relatively expensive technology. On the contrary, wind onshore capacity reaches its potential limit of 174 GW in SCOPE SD in all scenarios and is also strongly expanded in REMod and Enertile. In the latter, however, solar PV capacities are identical in all scenarios, while in REMod and SCOPE SD they are lower in the “low” scenario than in the “med” and “high” scenarios. The proportionally higher share of solar PV capacity compared to the amount of electricity generated results from their lower full load hours.

When covering the hydrogen demands in the different sectors, a key

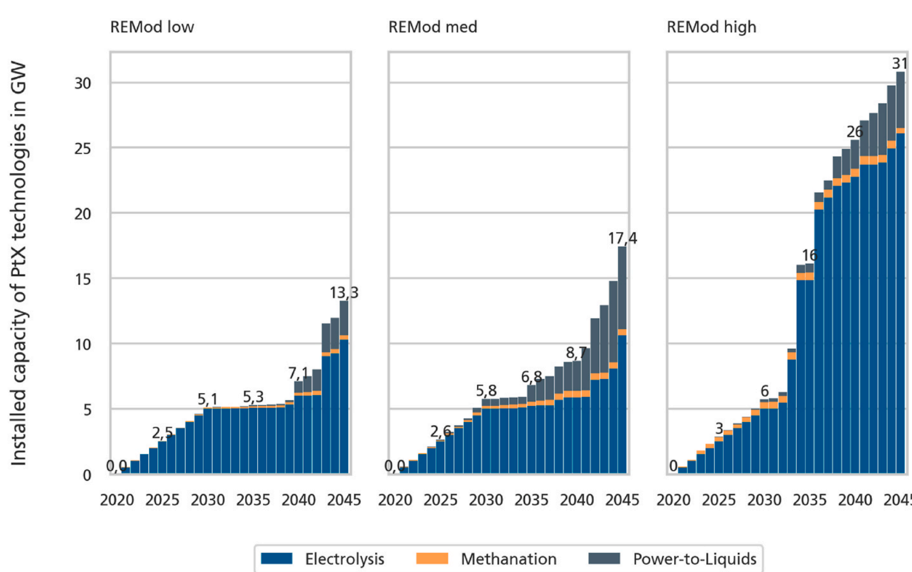


**Fig. 7.** Transformation pathway of installed electrolyser capacities as well as of methanation and PtL technologies in Germany in GW, own illustration.

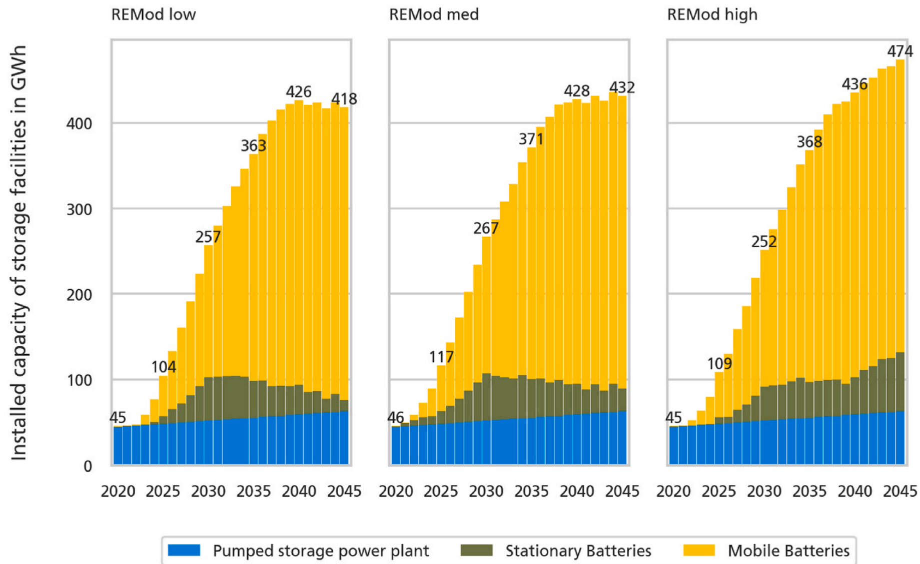


**Fig. 8.** Transformation pathway of installed capacities of storage technologies in Germany in GWh, own illustration.

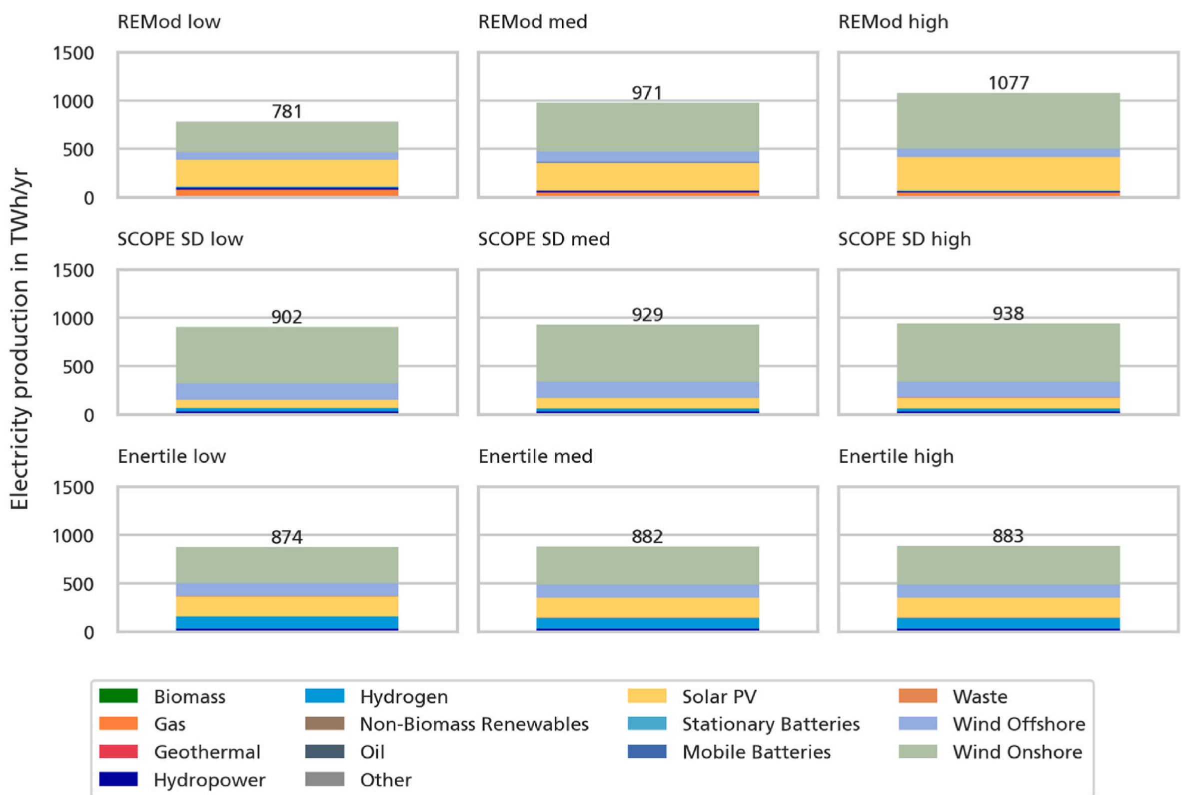


**Fig. 9.** Comparison of electricity generation volumes in Germany in 2045 in TWh/yr, own illustration.

question for the German energy system is the origin of that hydrogen, e. g. the trade-off between producing green hydrogen with domestic electrolysers and importing green hydrogen either from outside Europe or from other European countries. Fig. 11 shows the resulting hydrogen production and import balance for each scenario. Please note that the "Hydrogen import"-bar does not distinguish between European and non-European imports.

The total amount of hydrogen used in all models is highest when the import price is low. The amount of hydrogen produced from domestic electrolysers in Germany increases alongside the import price in all models as higher procurement prices on global markets render imports less attractive. On the contrary, hydrogen imports become lower as the import price rises. It is noteworthy in SCOPE SD and Enertile that the total sum of hydrogen production and imports is lowest in the "med" scenario, although on a similar level as in the "high" scenario. This slightly higher demand in the "high" scenario is explained by a higher conversion of hydrogen to electricity, which in turn is necessitated by more expanded direct resistive heating rods and more electric vehicles in use since the price for renewable fuels is also higher in this scenario. Nevertheless, it must be noted that the demand for hydrogen in SCOPE

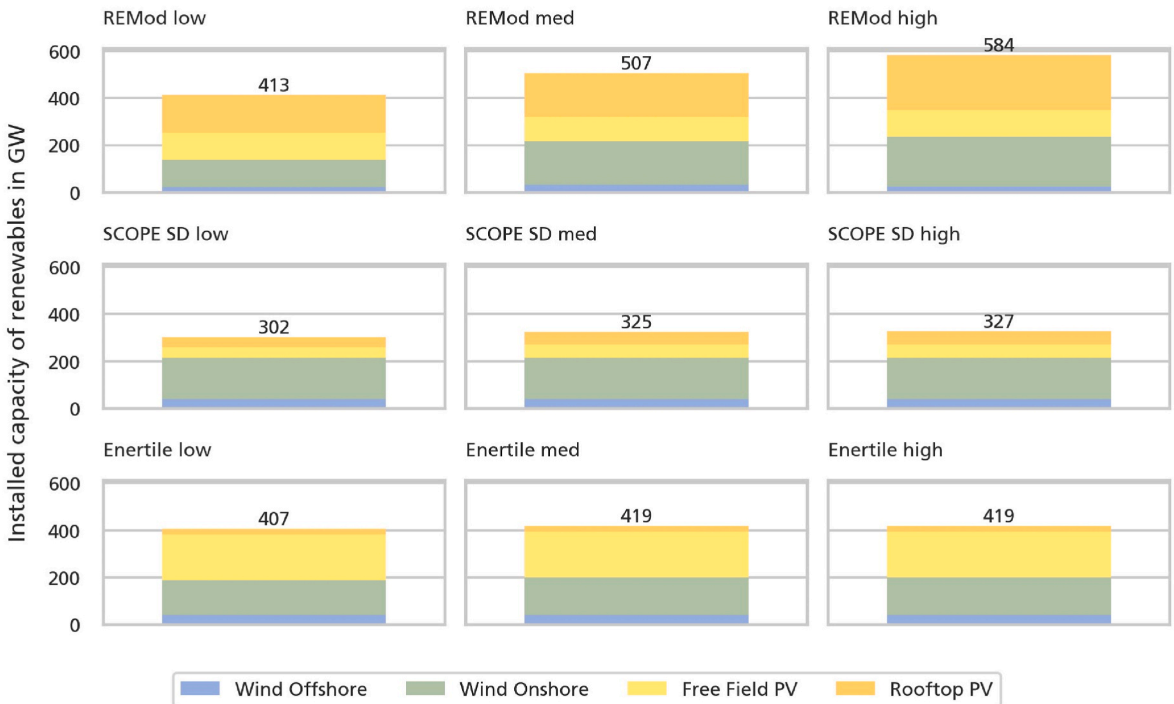


**Fig. 10.** Comparison of installed capacities of renewable energy technologies in Germany in 2045 in GW, own illustration.

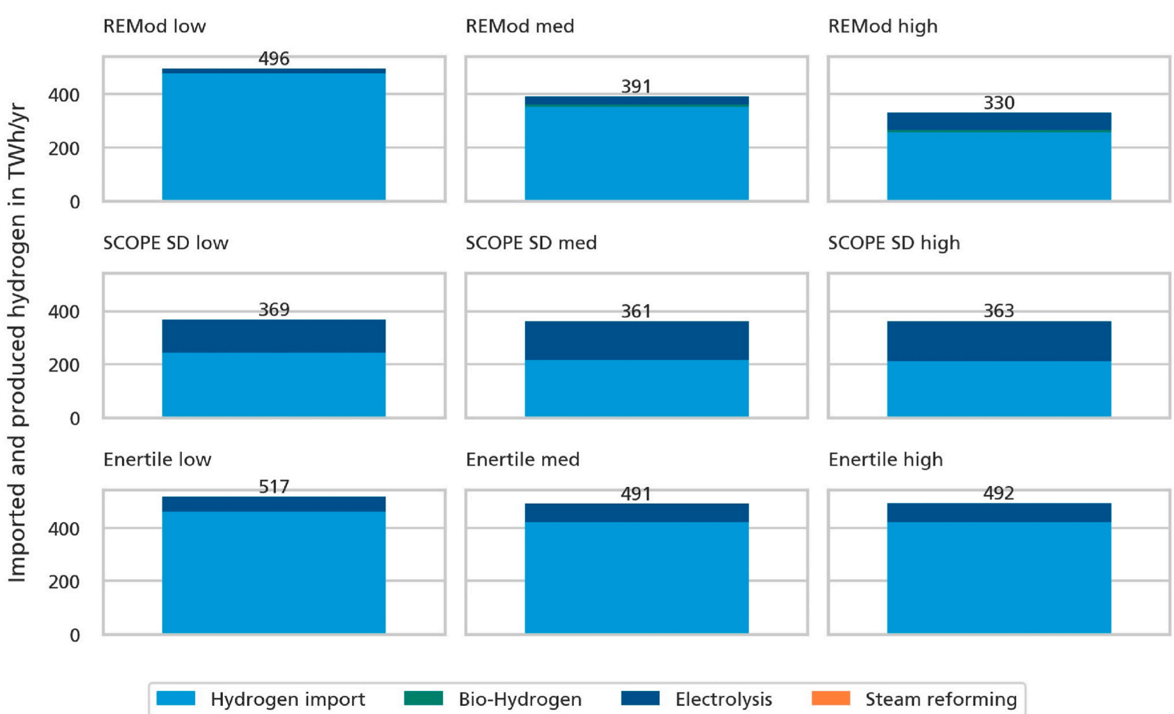


**Fig. 11.** Comparison of domestic hydrogen production and imports of hydrogen to Germany in 2045 in TWh/yr, own illustration.

SD and Enertile is overall very price inelastic, which can be explained by exogenous industrial demands and necessary conversion in power plants. Lastly, it should be mentioned that Bio-Hydrogen and steam reforming, which are only modelled in REMod, do not play a significant role.

The corresponding electrolyser capacities in Germany in 2045 are shown in Fig. 12. As expected, with higher import prices and thus a higher demand for domestically produced hydrogen, the required electrolysis capacities also increase in all energy system models. Particularly striking is the sharp increase of the installed capacity in REMod between the "med" scenario and the "high" scenario.

### 5.3. *Comparison of further effects on the German energy system and discussion of models*

The first differences between the models other than those that have

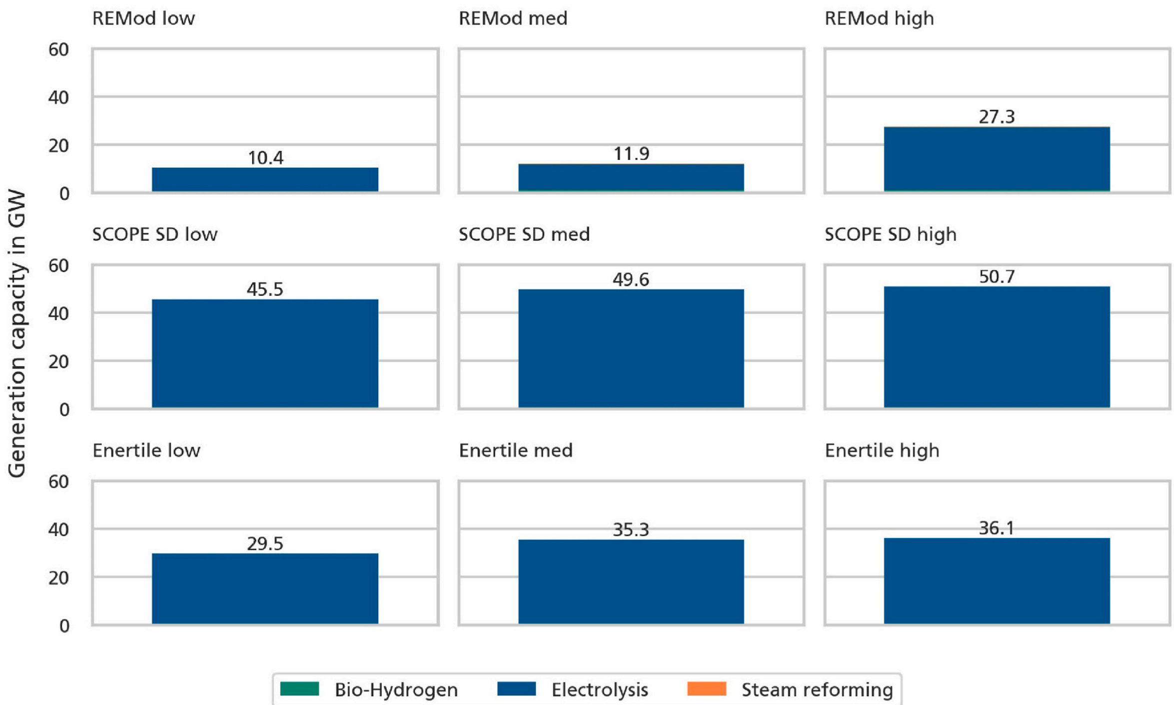


**Fig. 12.** Comparison of generation capacities in Germany in 2045 in GW, own illustration.

been shown in previous chapters become apparent in the expansion of battery storage capacities. While SCOPE SD does not build any battery storage in Germany in all scenarios, there is a constant expansion in Enertile and a higher expansion in REMod with an increasing hydrogen import price. This higher expansion of battery storage capacities in REMod is explained by the fact that there is less flexibility in using cross-border trade with Germany's neighbouring countries.

The use of pumped storage power plants is exogenously given in Enertile and is almost identical to REMod in all scenarios. In SCOPE SD, however, there is less pumping and withdrawal in pumped storage power plants at a higher hydrogen import price. This is once again because electricity becomes a more valuable commodity, and therefore pumping and withdrawal, which are associated with losses due to pumping efficiencies, are avoided as much as possible.

As the hydrogen import price rises, electricity imports to Germany behave in the opposite direction in Enertile and REMod on the one hand and in SCOPE SD on the other. In Enertile and REMod, electricity imports increase as the hydrogen import price rises. While in Enertile more imports arise from countries with cheaper generation costs, in REMod the implemented possible range of electricity imports is further used to full capacity, while the costs for these imports do not change in the model. In SCOPE SD, in turn, electricity imports decrease as the hydrogen import price increases. Here, the lower electricity generation from hydrogen is not compensated by higher imports, but by a further expansion of solar PV (recall Fig. 10).

Although the demands for electricity and renewable fuels in the transport sector are largely specified by other upstream models, they are implemented as upper and lower limits in the energy system models used here, so that shifts in demand are possible. In this context, renewable fuels (based on PtL processes) are considered necessary in long-distance transport. In particular, SCOPE SD and REMod show the effect that when renewable fuels are available more cheaply, more renewable fuels are consequently used in the transport sector. Thus, the cheaper these renewable fuels are, the lower the electricity consumption in the transport sector becomes, as fewer BEVs and PHEVs and therefore more PtL vehicles are used instead.

As mentioned earlier, with electricity becoming more valuable, renewable electricity curtailment decreases as the hydrogen import price increases in all models. Similarly, a slight increase in electricity demand in the heating sector is evident in all models, as more electricity-based technologies such as heat pumps or direct resistive heating rods are expanded. There are no occurring differences in the industrial sector since the demand for hydrogen was exogenously given in all models.

When interpreting the results, it should be considered that all of the applied models are cost optimisation models. This means that results reflect an optimum, which may be difficult to achieve in the real world. Neither of the model considers specific economic parameters such as taxes, levies, charges or profits of companies, which may change output in the real world. There are also some limitations of the individual models. While REMod focuses on Germany, there is only a limited representation of the European energy system and potential exports and imports. SCOPE SD relies on perfect foresight of the entire weather year and does not contain modelling of market power and successive decisions. Similarly, Enertile assumes perfect foresight and perfect markets. Additional analyses using simulation approaches could be realised in order to get a more realistic picture of real world behaviour.

## 6. Summary and conclusion

The analysis in this paper explores the impact of three different import price scenarios for hydrogen and its derivatives on the German energy system in a climate-neutral setting for Europe using three different energy system models. The observed insights show that the electricity generation volumes as well as the installed capacities for electricity generation and electrolysis are lowest in the low price scenario in all models. As the import price of hydrogen rises, the quantities of electricity produced also rise in all models, mainly because of the corresponding higher demand of electrolysers. The same holds true for electricity generation and electrolyser capacities.

The expanded electrolyser capacities suggest that domestic German (and European) hydrogen production is often cost-efficient. The high similarity of the medium price scenario and the high price scenario in the European modelling with Enertile and SCOPE SD leads to the expectation that a further increase in import prices would have no further impact, whereas greater differences occur in the low price scenario when the import price is lower than the costs of domestic hydrogen generation through electrolysis. However, the occurring differences in the results indicate that various aspects must always be considered when interpreting studies on the German energy system, namely the level of detail in Germany's integration into Europe, the distinction between endogenously and exogenously modelled sectors, and whether a transformation pathway is modelled or not.

Concerning limitations of the study it should be noted that the models make simplifying assumptions to represent integrated energy systems. The perfect foresight in the models does not correspond to the energy markets in the real world since non-perfect market efficiency and irrational behaviour must always be considered. As already mentioned in previous chapters, there are also several uncertainties in determining import prices for hydrogen and its derivatives. Since the comparison of the results in this study was based exclusively on Germany, a comparison of the energy systems of other European countries lends itself to further analysis.

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## Data statement

The case study result data for the German energy system are available in the open-access repository "Zenodo" at https://doi.org/10.5281/zenodo.8307808.

## 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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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.03.210.

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