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HYPAT Working Paper 01/2023

Price-Elastic Demand for Hydrogen in Germany - Methodology and Results

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April 2023	02	new disclaimer, clarification of the calculation of necessary electrolysis capacities

Disclaimer

Contents

1 Introduction

Today's hydrogen industry is currently still a sector without significant national and international trading activities. Only five percent of the globally produced hydrogen is transported and traded at the moment (see Monopolkommission 2021). At present, most of the hydrogen is produced either by industrial gas suppliers or on-site at the point of demand in the industrial companies that use it. As a result, there is no market for hydrogen, and the prices are usually not made public or are not available in bilateral contracts in the sense of a free public market.

However, hydrogen demand is expected to increase strongly in the future according to a large number of studies, in order to meet the ambitious reduction targets for greenhouse gases[1]. There will also be a strong increase in the number of potential applications in industry, heat and mobility. The political relevance assigned to hydrogen is apparent in the Hydrogen Strategies of Germany (Bundesregierung 2020) and the EU (European Commission (2020). The market roll-out of hydrogen requires significant investments in production capacities as well as in transportation and distribution network infrastructure, and realizing these will take time (see Ueckerdt et al. (2021)). Over the next few years, therefore, hydrogen is likely to remain a scarce and, in comparison to other energy sources, expensive commodity (see Wietschel et al. (2021a), SRU (2021)). This raises the question of where, i.e., in which applications, hydrogen will be used first. This depends heavily on the future price of hydrogen, which is why this constitutes a key research question.

Current knowledge suggests that hydrogen use is driven strongly by the ambition of greenhouse gas reduction targets (see Wietschel et al. (2021a) and Riemer et al. (2022)) and, in individual applications, by alternative solutions to reducing greenhouse gases (GHG), among others. There are large differences here between individual application sectors. These are also reflected by the analyses of GHG mitigation costs, which range from zero to more than a thousand euros depending on the application (see Ueckerdt et al. (2021)). It can be concluded from this that the willingness to pay for hydrogen could also vary considerably among individual applications.

Against this background, this Working Paper aims to develop and apply a methodology to generate a long-term price-elastic demand for hydrogen in Germany up to 2045. This includes analyzing which applications are characterized by high price elasticity and which by low price elasticity. This makes it possible to calculate the demand for hydrogen as a function of the assumed price developments.

Priority is given to direct hydrogen use in industry (material use, energy use in high-temperature processes), transport (especially road transport) and the conversion sector (for storage and reconversion into power or heat) (see Wietschel et al. (2021a), Riemer et al. (2022)). This paper therefore focuses on the model-based investigation of price elasticities in these three sectors. Hydrogen use is also being discussed for heating buildings, but as this is not always seen as a necessity, the building sector is only considered here using a simplified approach.

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[1] See, e. g., JRC (2019), Quarton et al. (2020), Wietschel et al. (2021a), World Energy Council (2021), Riemer et al. (2022), Fraunhofer ISI et al. (2022).

The working paper is structured as follows: Chapter 2 lays the foundations. This includes addressing the theoretical basis for determining hydrogen prices, a literature review of existing approaches in this field, and the competition facing hydrogen in the different application sectors. The chapter closes with an overview of the developed methodology and the presentation of methodological details in the individual application sectors as well as important framework conditions and data input.

Chapter 3 discusses the results obtained with the developed methodology in more detail. Chapter 4 gives a critical appraisal and an outlook to further research. The final Chapter 5 contains a summary with conclusions.

This working paper describes a methodological aspect of the HYPAT project. HYPAT is developing a global atlas of hydrogen potential and, for the first time, comprehensively identifying possible partner countries of Germany for the cooperative development of a future green hydrogen economy, including the importance of the regions producing hydrogen for a secure, economic, and environmentally sustainable supply.

2 Methodology to Determine a Price-Elastic Demand for Hydrogen and its Application to Germany and the EU

2.1 Review of existing methods

As outlined in the introduction, there are no historical, empirical data with which to derive a price for hydrogen as a function of supply and demand. There is therefore the need to rely on models or other methodological approaches able to develop price scenarios for the future. A literature search found only a few sources, which indicates a gap in the research on this issue.

Blanco et al. (2018) show how to model a price-elastic demand function for hydrogen. Blanco et al. use the cost optimization energy system model JRC-EU-TIME to explore the application of hydrogen in all sectors for different scenarios with up to 95% CO_2 reduction in 2050. The model maps the different options for meeting the demand, e.g., for steel, using different production processes and evaluates them based on the costs of a process. A price-dependent demand curve for hydrogen is plotted for each scenario. A constant hydrogen price is defined and the model decides endogenously how much hydrogen is demanded in which application areas at this fixed price. A demand curve can then be plotted using the different, exogenously specified hydrogen prices. If one of the parameters used to create the hydrogen demand curve is changed, the demand curve also changes. The demand function created in this way is then integrated into a cost-optimizing energy system model, which calculates hydrogen's supply coverage by having the different production options compete with each other.

NREL (2021) develops another methodological approach with long-term price elasticities on the supply and demand side. This calculates a hydrogen demand curve for different scenarios in the USA. For the analyzed application sectors, marginal prices (willingness to pay) are determined for hydrogen, above which hydrogen becomes competitive to alternative technologies. For instance, hydrogen is an essential feedstock for ammonia production with limited or no alternatives, so it is assumed that consumers here are willing to pay a higher price. The authors therefore set the marginal price of 3.00 USD/kg hydrogen for this application in the reference scenario. In steel production, on the other hand, hydrogen competes with natural gas in the direct reduction process. Depending on the price scenario for natural gas, the authors set the price for hydrogen at 0.80 USD/kg or 1.40 USD/kg. In total, nine applications are considered for hydrogen. For each application, a marginal price and the potential demand quantity are estimated. This estimation is based on expert assessments and by merging the results of studies. The price-elastic demand curve is created by aggregating across all applications. A cost-based supply curve for hydrogen is obtained for the USA using a comparable methodology. The costs of producing hydrogen using different production technologies such as electrolysis or natural gas reforming are determined using expert and study-based analyses, and the potential is quantified using the feedstock, i.e., the amount of renewable electricity generation or gas volumes available. The conducted analyses are static for the year 2050. The pathway up to 2050 is not considered.

2.2 Overview of the developed methodology

The objective of the methodology is to determine a long-term, price-elastic demand function. This means that investment decisions are taken into account and the total costs over the lifetime of the investments are considered. Determining a price-elastic H_2 demand requires detailed knowledge of the overall demand development in the individual fields of applications, the available technological options (see Appendix) and the economic evaluation. The investments and the running costs of the hydrogen application compared to the alternative options determine whether hydrogen is used. The willingness to pay for hydrogen is derived from this.

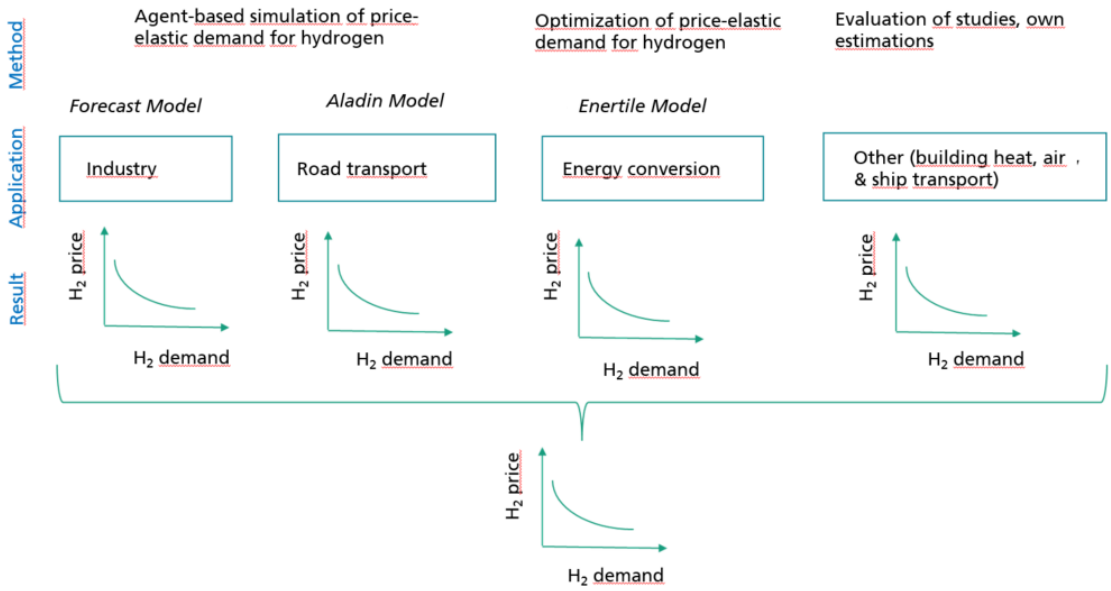
In recent years, Fraunhofer ISI has developed agent-based simulation models for this purpose for industry and the transport and heat sectors. These models are designed to develop scenarios of demand development for energy carriers in the individual sectors and to calculate greenhouse gas reduction scenarios. The drivers of demand, such as the development of the population, the gross national product, and the number and size of households are usually taken from other studies.

A number of technical and economic parameters are used as input to the analyses. These concern, on the one hand, the technologies mapped in the models (e.g., in the truck sector, conventional diesel trucks, fuel cell trucks, battery-electric trucks etc.), which compete with each other. On the other hand, framework parameters such as energy prices are stipulated. One parameter is the future price of hydrogen. Its variation in the scenarios determines the demand for hydrogen in the sector at each defined price level. The sector of heat in buildings is not analyzed using its own model, instead, information is drawn from other studies. It is important to note that this presumes an underlying scenario - including a number of assumptions - and that no projection is made.

An additional potential demand for hydrogen can emerge in the energy conversion sector, where, among other things, hydrogen can be used as a long-term storage option and be reconverted into electricity if required, e.g., in dark doldrums situations. To analyze these kinds of applications, optimizing energy system models have become well established over the years as a suitable methodology. This type of model is therefore used to determine a price-elastic demand in the energy supply sector.

An overall price-elastic demand function is then obtained through aggregation across all sectors. Figure 1shows an overview of the methodology.

Figure 1: Overview of the developed methodology



Source: own representation

The following analyses rely primarily on the model versions used in the Long-Term Scenarios, an ongoing study on behalf of the German Federal Ministry for Economic Affairs and Climate Action (BMWK) (see Fraunhofer ISI et al. (2022)). They are based on the T45 Scenarios, which assume greenhouse gas neutrality for Germany in 2045. This sets a very significant framework condition for the following modeling results, because greenhouse gas neutrality is a strong driver for the transformation of the energy system, also in terms of the use of hydrogen. Numerous studies have shown that hydrogen is only used on a larger scale under greenhouse gas reduction targets of 80% and higher (see the meta studies in Wietschel et al. (2021a) and Riemer et al. (2022)).

Three main scenarios are calculated in the Long-Term Scenarios project:

- Strong use of electricity (Scenario T45-Electricity)
- Strong use of hydrogen (Scenario T45-H_2)
- Strong use of synthetic hydrocarbons (T45-PtG/PtL)

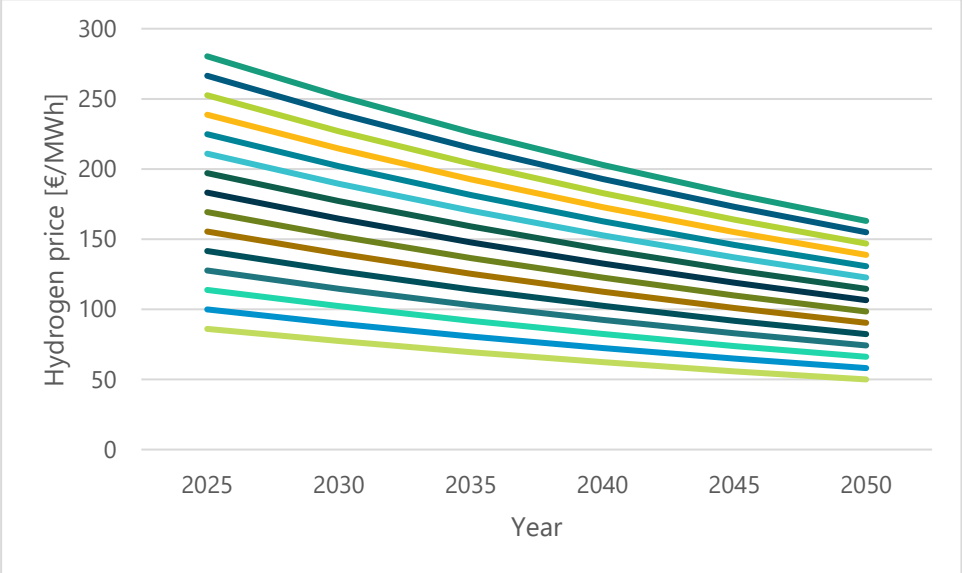
In terms of method and content, a learning process is conducted in the Long-Term Scenarios to shed light onto the solution space for a greenhouse gas-neutral energy system, in this case, to illuminate the three 'corners' of the solution space. To do so, optimistic assumptions are made in the three scenarios regarding techno-economic parameters such as investments, service life, infrastructure availability etc. with regard to the respective corner that is to be illuminated.

The following analyses are based predominantly on the assumptions of scenario T45-H_2, but deviate from them in several points, which are addressed in the next chapters.

2.3 Assumed price scenarios

When modeling a price-elastic demand function for hydrogen, different hydrogen prices have to be set. These must be available as future price pathways from the present up to the end of the analysis period (2050). A static analysis of one point in time is not sufficient, because investments in the years leading up to this point, e.g., in direct iron reduction based on hydrogen, influence the results (path dependencies). In addition, it can be strongly assumed that hydrogen prices are higher to start with and then decrease over time due to economies of scale, among other things. Figure 2 shows the price pathways assumed in the following analyses, which cover a wide range of possible developments. These were derived from a number of studies (see Deutsch et al. (2018), Pfennig et al. (2017), Timmerberg et al. (2019), Prognos (2020), Lux et al. (2021), Hank et al. (2020), Hydrogen Council & McKinsey (2022), Hobohm (2018) and Hampp et al. (2021)).

Figure 2: Analyzed price pathways (wholesale) of hydrogen



Source: own representation

It should be emphasized that these are wholesale prices. Additional costs include those for national transportation, storage and distribution, as well as taxes and levies and, in the case of transport, expenses for fueling stations as well.

The work here stands out due to its analysis of price pathways over time, because comparable studies usually only consider a single point in time.

When looking at the analyzed price pathways, very low price pathways should be critically appraised. There are studies of the manufacturing costs and demand quantities in greenhouse gas neutral scenarios, from which production costs can be derived if demand is met. If this is done, it becomes clear that the production costs in the two studies Hydrogen Council & McKinsey (2022) and Pfennig et al. (2021) range from 60 to 90 €/MWh H_2 in 2045/2050. This makes it clear that such market price assumptions are rather unlikely according to current knowledge.

2.4 Modeling Industry

2.4.1 Introduction

Motivated by climate and energy crises, decarbonizing the energy demand of industry is a major driving force for the transformation of entire value chains and individual production processes. Industry consumes about 30% of the final energy in Germany (AGEB 2019) - slightly less than the transport sector and slightly more than the household sector - and accounted for 24% of German greenhouse gas emissions in 2021 (calculated using figures from UBA (2022a)). The material use of energy carriers in the chemical industry is in addition to this. The sum of this demand in 2019 amounted to around 950 TWh. In addition to direct electrification, the use of hydrogen as an energy carrier is being discussed as a possible solution in a wide variety of industrial applications (see Appendix).

In order to prioritize these applications in terms of price elasticity, their techno-economic characteristics have to be considered. These include - in addition to the actual purpose of the application (energy or material) - the temperature level provided, the development stages of the specific technologies and their alternatives, as well as economic variables (e.g., CO_2 avoidance costs). This type of subdivision makes it possible to order applications by their suitability and attractiveness for hydrogen use.

This type of prioritization is done in the following section and the resulting demand for hydrogen in industry is carried out using a scenario-based model at several price levels.

2.4.2 Methodology

2.4.2.1 Modeling overview

Modeling the demand scenarios for industry is done using the bottom-up simulation model FORECAST. A more detailed description is available in Fleiter et al. (2018). Two features are especially relevant to understand the procedure followed here: The basic reference variable of industrial activity is the physical production of energy-intensive products, for example in tonnes of raw steel, cement or ethylene. These volumes are determined exogenously as part of the scenario definition and based on past developments. Over the course of the scenarios, the processes that can potentially be used for these products change - for instance, the production of steel in blast furnaces is replaced by hydrogen-based direct reduction if this leads to the desired result and is possible under the given assumptions. These developments concern the most important basic materials that are produced in dedicated sites and plants and are of outstanding importance for both energy demand and greenhouse gas emissions. In addition to this, the modeling also includes the competition between energy carriers. The model simulates the switching between fuels (and electricity) based on economic attractiveness, which is predominantly determined by the price of energy carriers. Usually, the share of an energy carrier in total energy use increases if it becomes less costly compared to other options.

These two features of the model are incorporated into the scenarios calculated here. The following sections describe the concrete implementation and the associated framework conditions and constraints.

2.4.2.2 Implementation and parameterization

Fifteen hydrogen price pathways are entered into the model (see section 2.3). This is done in two steps: The exogenous definition of production quantities, and the endogenous competition between energy carriers. As mentioned above, the scenarios' fundamental setup (energy carrier prices apart from hydrogen, CO_2 pricing, economic development) is based on the T45-H_2 Scenario of the Long-Term Scenarios (Fraunhofer ISI et al. 2022).

The **exogenous estimation of production volumes** is based on considering the differential costs of conventional (fossil) production processes and their hydrogen-based alternatives[2]. This is done by comparing the energy, CO_2- and investment-related costs of the reference technology (e.g., blast furnace route) with the alternative route (here, H_2 DRI). The resulting difference - if the alternative route is more expensive - is compensated by accessing existing funding programs (Carbon Contracts for Difference (CCfD), Decarbonization of Industry Program, IPCEI, and others). Higher hydrogen prices generate higher differential costs - placing a heavier burden on funding budgets. The production volumes of alternative processes that are able to be funded (e.g., 10 Mt H2 DRI steel by 2030) therefore result from the differential costs and the available funding budget (see Projection Report (Repenning et al. 2021) and climate protection instruments scenario (2030)). These are entered into the model. In this approach, the allocation of the funding budget is necessarily arbitrary to a certain extent, other allocations are also conceivable. However, other framework conditions limit the solution space.

These framework conditions include a requirement that all scenarios or price levels should achieve the climate goals of the German government (2030: 58 % reduction compared to 1990 (118 $Mt_{CO2\text{-}eq.}$ annual emissions), 2045 extensive decarbonization and substantial contribution to Germany's greenhouse gas neutrality). This basically predicts two developments that are correspondingly assumed for the modeling. There is already a strong shift in crude steel production towards hydrogen-based direct reduction by 2030 (necessary to achieve the target for 2030), and the chemical industry does not use any fossil raw materials by 2045 at the latest. This framework condition overwrites the available funding budget. If, therefore, more funding is needed at higher H_2 price levels to achieve the climate goals than is earmarked in the budget, the budget will be overdrawn.

The **model-endogenous competition between the energy carriers** is represented by adjusting the price signal for hydrogen at each price level to the respective pathway considered. The use of hydrogen to generate process heat (steam and industrial furnaces) becomes more attractive at each lower price level and can better prevail against competing energy carriers (biomass, electricity and - during the transition to full decarbonization - fossil energy carriers).

Together, these two effects - shifting production volumes to new processes and switching energy carrier in process heat - map the price-sensitive demand for hydrogen. Pairs of values for price and demand result for the price levels.

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2 This method was also used in the Projection Report 2021 (Repenning et al. 2021) and the Climate Protection Instruments Scenarios (KIS-2030, under publication); the scenarios are based on the landscape of policy instruments used there to transform industry.

2.5 Modeling Transport

2.5.1 Introduction

The transport sector was responsible for 19% of the GHG emissions in Germany in 2021 (calculated using figures from UBA (2022a)). In the past, this sector has not decreased its emissions, any technical efficiency gains are compensated for by increased traffic volume and vehicle size. The transport sector must make a relevant contribution to lowering greenhouse gases in the future if Germany is to achieve its goal of becoming greenhouse gas-neutral in 2045.

Hydrogen can be used for a range of applications in the mobility sector. Fuel cell vehicles are already commercially available in the passenger car segment in the first small series, and they are in regular operation in the area of transporting materials, for example in forklift trucks. In addition, there are fleet trials in the bus transport sector (local and long-distance) in Germany. In the truck segment, especially for medium and heavy-duty trucks, several activities are already taking place and the production of a very small series is planned in the near future. In rail transport, there are the first fleet trails or announcements of non-electrified track sections.

There are restrictions on hydrogen vehicles in applications where very high energy density is required, such as international air and sea transport. Here, synthetic hydrogen-based fuels or biogenic-based fuels will play an important role in lowering GHG emissions in the future. On the other hand, there are applications where energy density requirements are not high. Here, battery-electric options dominate for economic reasons now and will probably continue to do so in the future as well, such as in micromobility, bicycles and small and medium-sized cars. According to the Hydrogen Council (2020) study, the following applications are the most promising areas for using hydrogen in combination with fuel cells (FC) based on current knowledge: Medium and heavy-duty trucks, long-distance coaches and long-distance buses in urban environments, large passenger cars and SUVs with high range requirements, taxi fleets, regional trains, and forklift trucks.

A price-elastic demand for cars and trucks is calculated using an agent-based model. For air and sea transport, an estimate is made based on the current Long-Term Scenarios Study (see Fraunhofer et al. (2022), Gnann et al. (2022)).

2.5.2 Methodology for cars and trucks

2.5.2.1 Modeling overview

The simulation model ALADIN (**AL**ternative **A**utomotive **D**iffusion and **IN**frastructure) is used to model powertrain-specific transport demand and specifically the influence of the hydrogen price on the demand for hydrogen. This is an agent-based model that represents the purchasing decision of individuals under given framework conditions. The purchase decision is simulated on the basis of real-world driving profiles and their resulting requirements. For each driving profile, the drivetrain technology is selected which maximizes utility. Finally, the individual purchase decisions are merged in a stock model.

ALADIN has already been applied in various national and international studies (compare, for example, Plötz et al. (20214) and Gnann et al. (2015)). Basic information about the model, reference projects and publications can be found at www.aladin-model.eu. Reference is also made

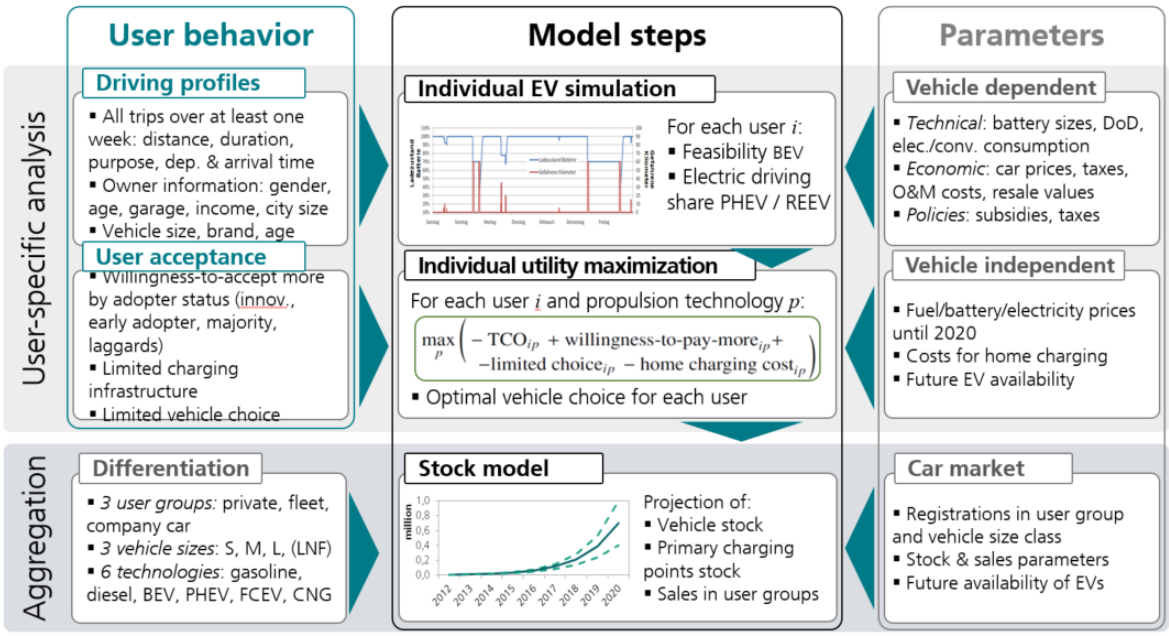
to the T45-Electricity Scenario, which was developed in the current Long-Term Scenarios study (Fraunhofer ISI et al. 2022).

ALADIN distinguishes six alternative powertrains for passenger cars <3.5 t GVW: (1) Gasoline, (2) Diesel (both based on crude oil or synthetic liquid fuels), (3) Gas (NGV, both natural gas and synthetic gas), (4) Plug-in hybrids (PHEV), (5) Battery-electric vehicles (BEV) and (6) Fuel cell vehicles (FCEV).

Seven alternative powertrains are distinguished for commercial vehicles: (1) Diesel (2) Gas, (3) Plug-in hybrids (PHEV), (4) Battery-electric (BEV), (5) Fuel cell and two types of overhead catenary vehicles, which are equipped either with (6) an additional battery (O-BEV) or (7) an additional combustion engine (HO-Diesel).

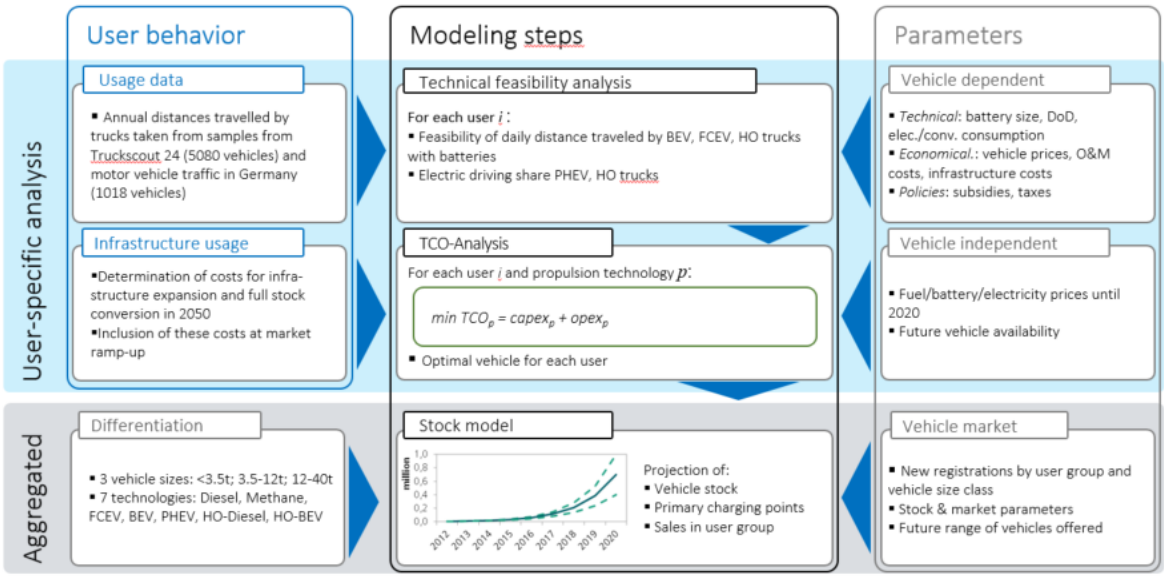
The model provides a market evolution of alternative powertrains as an output for each size class. Figure 3 and Figure 4 show the model's most important input and output data for cars and trucks. A detailed model description is also available at https://www.aladin-model.eu/.

Figure 3: Overview of the procedure in ALADIN for passenger cars



Source: Fraunhofer ISI (2023).

Figure 4: Overview of the procedure in ALADIN for commercial vehicles



Source: Fraunhofer ISI (2023).

2.5.2.2 Implementation and parameterization

ALADIN models passenger cars and trucks for this study. The parameterization of the model was based on the Long-Term Scenarios. Similar to the modeling of industry, the fundamental setup of the scenarios is based on the Scenario T45-Electricity (see Fraunhofer et al. (2022)). The hydrogen price pathway was added to this from section 2.3. In addition, the availability of infrastructure for overhead catenary vehicles was limited, and hydrogen infrastructure was adopted from the T45-H_2 Scenario of the Long-Term Scenarios.

2.5.3 Methodology for other mobility sectors

Rail, buses, ships and airplanes are considered as additional mobility sectors. This is not analyzed using its own model, but draws on existing evaluations, especially on the Long-Term Scenarios (see Fraunhofer et al. (2022)). The different options to reduce emissions are calculated on a techno-economic basis and GHG reduction scenarios are created based on the development of transport performance scenarios.

2.6 Modeling Energy Supply

2.6.1 Introduction

When viewed over the last two decades, there has been a significant reduction of GHG emissions in the energy sector. However, with 32% in 2021, it still had the highest share of GHG emissions of all sectors in Germany (calculated using data from UBA (2022a)).

Hydrogen is an important option in the conversion sector for providing flexibly controllable generation capacity, mainly due to its relatively good storage capability. This applies to the

supply of both electricity and heat in heat networks. Energy systems that are mainly or exclusively based on fluctuating renewable energies require supply options if renewable energy provision is low due to unfavorable weather conditions. Hydrogen can be an option to cover residual loads. In the power system, it competes with demand-side flexibility options, such as load management, and with other supply-side flexibility options, such as interregional load balancing via reinforced power grids. At the same time, there is cross-sectoral competition for the best-possible allocation of a relatively expensive energy source.

2.6.2 Methodology

2.6.2.1 Modeling overview

Hydrogen demand in the conversion sector is determined using the optimization model ENERTILE. ENERTILE determines the minimum-cost energy supply infrastructure for hourly coverage of predefined electricity, heat and hydrogen demand from the classic energy demand sectors industry, transport, tertiary (trade, commerce and services) and households. This infrastructure includes conversion and storage technologies for all the energy forms considered as well as simplified transmission networks for electricity. The model focuses in particular on the high technology, temporal and spatial resolution of renewable energy potentials. Individual model runs usually consider the European Union, United Kingdom, Norway and Switzerland for various reference years up to the target year of greenhouse gas neutrality.

Hydrogen plays a special role in the modeling. The optimization not only determines how exogenously specified hydrogen demand can be covered as cost efficiently as possible using electrolysis, but also to what extent hydrogen is used as a seasonal storage medium for the conversion sector itself. Under the assumption of perfect foresight and considering the costs of hydrogen production, storage and conversion, the model determines the hydrogen used to provide electricity and heat. PEM electrolyzers are parameterized for hydrogen production; conversion technologies are limited to hydrogen turbines for generating electricity and hydrogen boilers for generating heat.

2.6.2.2 Implementation and parameterization

The analyses in this paper are based on calculations published in Lux et al. (2020), which are limited to a greenhouse gas-neutral European energy system in 2050. In this case, the demand for hydrogen from the demand sectors was not modeled explicitly, but indirectly using the willingness-to-pay for electrolysis-based hydrogen. In this case, the cost minimization of the supply-side energy system determines the amount of hydrogen that can be provided at cost under the demand sectors' assumed willingness-to-pay. In a parameter study, different model runs assumed different levels of the willingness-to-pay for hydrogen of between 0 and 150 Euro/MWh. The "sale" of hydrogen to demand sectors always competes with its use in the conversion sector. The analysis applied here compares the model-internal shadow prices for hydrogen with hydrogen use in the conversion sector in different model runs.

2.7 Consideration of Building Heat

Using hydrogen in the heating sector remains controversial. Here, there are other alternatives available that are often regarded as economically more viable, including increased energy efficiency through better insulation, heat pumps and heating networks (see SRU 2021). This is why numerous studies show no or only low potential for hydrogen use in this sector (see meta-studies in Wietschel et al. (2021a) for Germany and the EU and Riemer et al. (2022) for global analyses). The possible use of hydrogen would then mainly be used to replace natural gas, which is a rather expensive mitigation measure to reduce greenhouse gases (see Ueckerdt et al. (2021)). This means that hydrogen will only be used here on a larger scale if its price is much lower.

An analysis of studies shows that hydrogen is unlikely to play a major role in heating buildings under the price pathways assumed here. A recent study on behalf of the German Hydrogen Council (Thomsen et al. 2022) uses concrete case studies considering the various options for supplying heat to households and industry to show that hydrogen will only play a relevant role if hydrogen prices are low. For space heating in buildings, even in the low price pathway assumed for hydrogen of 90 Euro/MWh (retail price, i.e., including distribution network costs), the study indicates that space heat will be provided mainly by heat pumps and district heating in areas with no or with only low demand for process heat for industry.

Knosala et al. (2022) come to a similar conclusion. Here, the role of hydrogen for climate-neutral energy supply compared to electricity-based systems in single and multi-family houses is investigated in a techno-economic study that considers renovation measures in residential buildings in Germany. The results show that a break-even price for hydrogen results from threshold values of 10 Euro/MWh for single-family houses and 50 Euro/MWh for multi-family houses.

It is also possible to approach this issue using a comparison to the gas price. For the gas price, it is assumed that hydrogen is fed into the natural gas network and displaces natural gas there. The applicable price for hydrogen is then the natural gas price plus the price of CO_2 allowances. In Frontier (2021), this approach is used to calculate an applicable hydrogen price of approx. 40 Euro/MWh for Germany. A comparable approach is taken in NREL (2021) for the USA. Current gas prices are currently well above 40 Euro/MWh, but they could return to a normal level in the long term, as assumed, for example, by the IEA in their long-term scenarios (IEA 2021a). As hydrogen is still predominantly produced using natural gas reforming at present, this is accompanied by correspondingly high hydrogen prices. Hydrogen produced using electrolysis is currently also very expensive due to high electricity prices.

Both approaches lead to values that are below the most cost-favorable price pathway assumed for hydrogen in this study (see section 2.3). Therefore, there is no potential for using hydrogen for heating buildings.

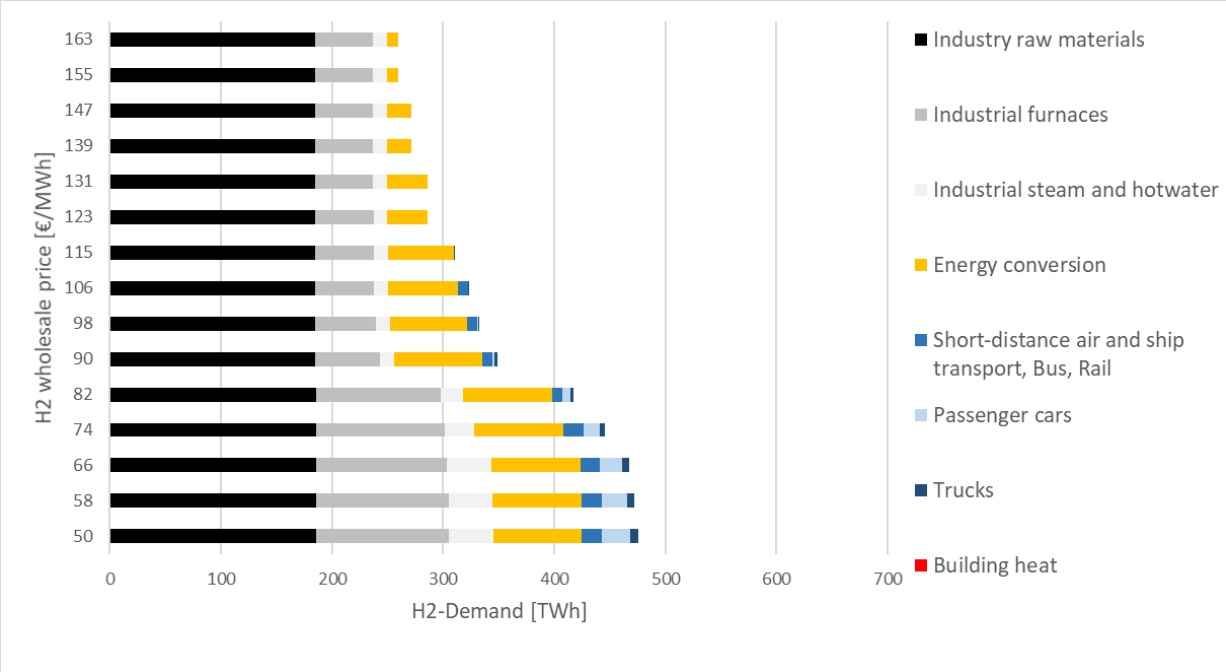
As a constraint, it should be mentioned that not all buildings can use heat pumps and efficiency measures, for example, due to noise reasons or because they are protected historical buildings. In addition, if hydrogen is already being supplied to industrial companies, this could lead to it

also being used in the vicinity to heat buildings. There is the potential for using hydrogen in such cases if it is available at very low cost. See also Thomsen et al. (2022).

3 Result: Price-Elastic Hydrogen Demand in Germany

Based on the methodology described above, the results of a price-elastic demand for hydrogen are now presented in the scenario of being greenhouse gas-neutral in 2045. Figure 5 shows the results of modeling a price-elastic demand in 2045.

Figure 5: Price-dependent hydrogen demand in Germany under the target of greenhouse gas neutrality in 2045



Source: own representation

It can be concluded that there is high demand for hydrogen in price-inelastic areas in industry (material use, process-related use and energy use in niche applications). In addition, there is lower demand that is more price sensitive in energy supply (storage and reconversion into electricity) as well as demand that only occurs at very low prices (energy use in industry, in mobility for cars, trucks, buses and rail). These individual areas are now addressed in more detail.

Based on high price pathways for hydrogen, the industry simulation shows an initial robust demand for hydrogen of about 250 TWh. This is not price-sensitive and reflects the framework conditions set in the scenarios that climate goals must be met. This concerns the use of hydrogen for raw materials (chemicals, 184 TWh for prices up to 90 Euro/MWh) and industrial furnaces (hydrogen-based steel production, 55 TWh for prices up to 98 Euro/MWh), which emerges because there is no known alternative that can do without hydrogen and that has sufficient technology and economic readiness. In this area, the price inelasticity indicates that there are very high GHG reduction costs and that high state subsidies are needed to maintain domestic production so that this can compete internationally or if alternative products become available. Only at hydrogen prices of less than 90 Euro/MWh does the need for subsidies decrease significantly and additional demand is induced for other energy applications in industry.

Another approx. 100 TWh will be added in 2045 up to the lowest price level. This will be supplemented by the use of hydrogen in industry to generate steam (demand of up to 40 TWh).

In the transport sector, there is a high demand for hydrogen of 209 TWh in the form of synthetic fuels for international air and maritime transport. As mentioned above, in the Long-Term Scenarios, it is assumed that this is covered by existing biomass potentials (Fraunhofer ISI 2022). This is why this is not illustrated in Figure 5. Similar to certain industrial applications, there are no alternatives here at present to reduce emissions.

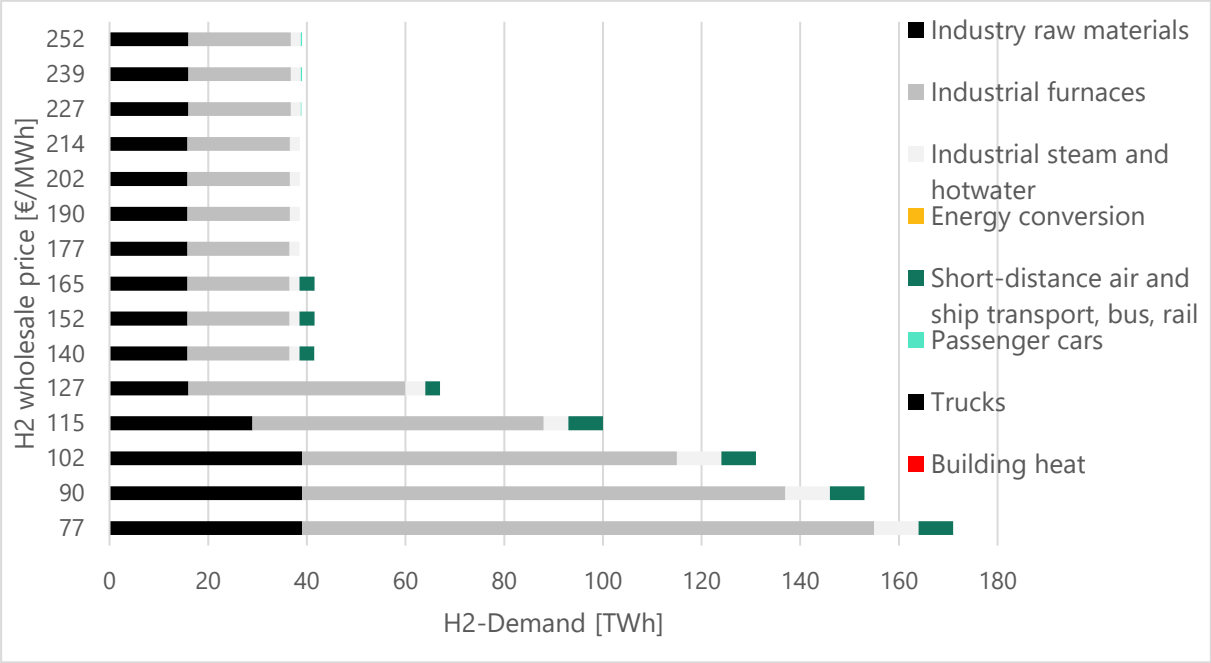
A direct use of hydrogen for other mobility applications is only foreseen at very low prices. These include hydrogen use in fuel cell cars and trucks as well as in buses and on rail sections that are not electrified at present, and in air and maritime transport over distances of less than 1000 km (52 TWh in total at the lowest price level). If low H_2 prices are not assumed in the calculations, predominantly direct electrification with batteries is assessed as economically more viable.

The reaction of demand to price variations is stronger in the energy conversion sector than in industry or the transport sector. This is due to the fact that there are a number of alternatives here. If hydrogen prices are high, it is cheaper to deploy more renewables and accept electricity surpluses and to use more electricity in heat networks. Therefore, if prices are high, the demand for hydrogen can be very low, although there will be some demand to cover dark doldrum situations, even if this is low. If hydrogen prices drop, its use in the energy system becomes increasingly attractive and can amount to 80 TWh at the lowest price level.

It must be noted for these results that some of the demand for hydrogen and its derivatives could also be substituted by biogenic sources. The Long-Term Scenarios allocate the limited sustainable biomass available to international air and maritime transport, which require almost the entire biomass potential in Germany of 250 TWh in 2045 (Fraunhofer ISI 2022). This allocation is also adopted in this working paper. In scenarios of other studies (e.g., Agora and BDI), the limited potential of sustainable biomass is partially used in other sectors (industry, heat). The total available biomass potential is of a similar order of magnitude. Since international air and maritime transport also rely heavily on hydrogen or hydrogen derivatives for decarbonization, the demand curve depicted in Figure 5 would hardly change if the biomass potential were allocated to different sectors. Figure 8 in Appendix B shows the total price-elastic demand for hydrogen and biomass

Figure 6 shows the demand for hydrogen as a function of its price. Overall demand is quite low, especially at medium and high prices and is dominated by the demand from industry. Crude steel production already shifts strongly until 2030 to hydrogen-based direct reduction (necessary to achieve the target in 2030; total hydrogen demand for industrial furnaces of 21 TWh up to a price level of 140 Euro/MWh, at lower prices followed by a significant increase up to 116 TWh). In addition, 16 TWh of hydrogen for material use is calculated for prices down to 140 Euro/MWh. At low prices, direct hydrogen use is also seen in national air, shipping, bus and rail transport.

Figure 6: Price-dependent hydrogen demand in Germany under the target of greenhouse gas neutrality in 2030



Source: own representation

4 Critical Appraisal and Outlook

4.1 Critical appraisal of the approach

In general, it must be said for these kinds of studies that the results are strongly dependent on the framework assumptions made, such as climate policy goals, or the assumed development of techno-economic parameters, such as investments in direct iron reduction plants in the steel industry or their service life. Their future development is subject to uncertainties.

Feedback effects between supply and demand are not taken into account. For instance, additional demand for hydrogen covered by electrolyzers could lead to higher prices for electricity. This has repercussions on the competitive situation of hydrogen and electricity in the demand sectors. However, this effect is disregarded, as the electricity price is kept constant when developing the price-elastic demand for hydrogen in the chosen approach. These kinds of effects could be integrated into the methodology via scenarios with varying electricity prices.

It should also be noted that reactions with other energy sources are not considered, e.g., the effect of increased hydrogen demand in transport on gasoline and diesel prices. As an additional limitation, it should be mentioned that it is assumed that demand in the sectors does not shift abroad. This could actually be the case, especially at high hydrogen prices, e.g., in industry. This study assumes that politics sets the relevant framework conditions to keep industrial products in Germany. This must be viewed critically, especially in the high hydrogen price scenarios. It was also excluded whether higher hydrogen prices will also lead to a general decline in demand.

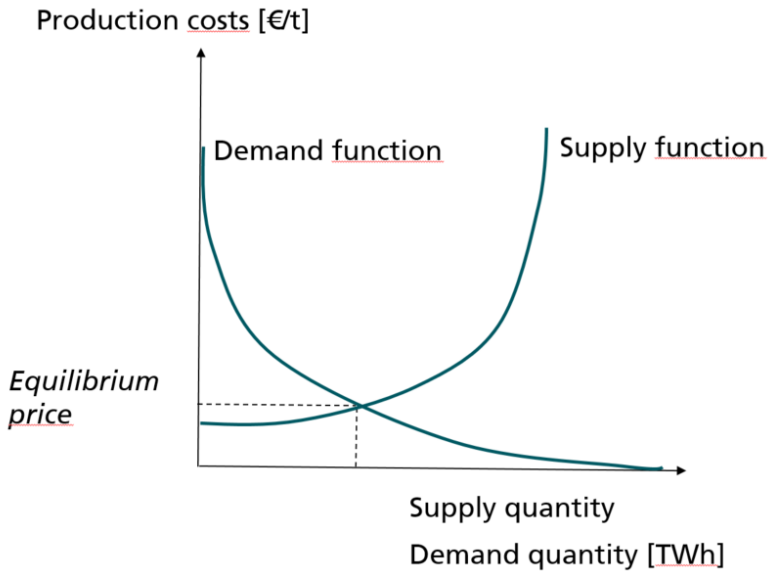
The analyzed applications did not include the use of hydrogen in cogeneration plants, although there may well be interesting potentials here (see Thomsen et al. (2022) and Fraunhofer ISI et al. (2022)). Further analyses should be conducted here on integrating these into the approach.

Carbon dioxide capture and storage (CCS) was largely excluded as a mitigation technology in the analyses. Studies with scenarios in which CCS is assigned a bigger role yield significantly lower demands for hydrogen and synthetic fuels (see study overview in Wietschel et al. 2021a). This would also mean lower hydrogen prices. CCS's potential role as a game changer should therefore be monitored carefully and analyzed further.

4.2 Outlook: Determining hydrogen prices and trade flows

At present, it is assumed that Germany, but also other countries such as Japan, will not be able to cover domestic demand for hydrogen themselves (see Fraunhofer ISI (2022) for the German situation, Wietschel et al. (2021a) for the German and European situation, Irena (2022) for the international situation). How hydrogen prices could be set and international trade flows could be established in the future is currently being explored in various studies and in HYPAT as well.

Figure 7: Price formation on perfect markets



Source: own representation

Partial equilibrium models distinguish between long-term and short-term approaches, which are differentiated by the expenses included. The long-term models assume long-term marginal costs, which include capital expenditures (CAPEX) and operating expenditures (OPEX). The short-term models only include operating expenditures.

The goal of long-term partial equilibrium models is to evaluate investment decisions for investors or to make strategy recommendations for political decision-makers. They are particularly suitable for Greenfield approaches, for which investments have not yet been made. This is the case for this issue of internationally traded hydrogen and trade flows. Short-term models are suitable for analyzing short-term price developments, but require existing production and transport systems to do so.

Partial equilibrium analyses can be applied to perfect competition, monopolistic competition, oligopoly, monopoly and monopsony, and can consider the effects of government interventions. This is important, because the information currently available suggests that market power, market organization and regulation could play a major role in hydrogen markets.

When looking at the studies on the topic of hydrogen, several have modeled the production costs of hydrogen or synthesis products on the supply side based on renewable electricity generation (see the overview of studies in Wietschel et al. 2021b). These studies determine the production costs for a real or assumed location. Other studies go further and determine the optimized production costs for all sites in a region or country and obtain a supply curve for hydrogen or synthesis products by sorting them in the ascending order of costs. A global, cost-based supply function is obtained by aggregating all the regions or countries considered. See the corresponding approaches in Pfennig et al. (2021), Forschungszentrum Jülich (2021), Brändle et al. (2021), Hydrogen Council & McKinsey (2022), and IRENA (2022). In some cases, these are compared with a fixed hydrogen demand, see, e.g., Lux et al. (2021), Schönfisch et al. (2022) and IRENA (2022). Possible trade flows between supply and demand countries can be determined by including the costs of transport and a demand for hydrogen, see, e.g., Heuser et al. (2019) or IRENA (2022). However, these studies do not make any statements about market

or price development, since they are limited to the analysis of production and transport costs and demand is assumed to be constant.

In addition to the approaches to determine production costs, there are other approaches based on partial equilibrium models (Schönfisch et al. 2022, Riera et al. 2021). In these approaches, each part of the supply chain (e.g., electrolysis, pipeline, ship transport, liquefaction etc.) represents an agent that wants to maximize its profits. They are based on full-cost considerations. These can be used, for example, to illustrate supply-side monopoly or oligopoly situations. While demand in partial equilibrium models is usually price-dependent, the models identified for hydrogen take a simplified approach and assume a price-inelastic demand.

The method presented in this working paper is therefore suitable for moving from the simplified assumption of inelastic demand to elastic demand in existing approaches. There are more details on this in Wietschel et al. (2021b). A long-term partial equilibrium model is currently being developed, which is able to determine price scenarios and trade flows.

One challenge here is the considerable amount of time and effort required to collect detailed price-elastic demand functions as carried out in this paper based on models for Germany. This implies that simple approaches might be required. One such approach is described in the following.

The general approach of using a long-term demand function can also be transferred to other regions and countries without detailed simulation models of the energy system. As in the energy system models, technology transition in the long run is driven by the ambition to mitigate climate change. As explained above, the decision on how to decarbonize a technology is mainly determined by the economic competitiveness of the various options. The necessary changes to decarbonized processes and options are driven by assumptions (e.g., greenhouse gas reduction pathways, demand for energy and industrial products). These required decarbonization measures further determine the amount of hydrogen required for energy use in all end-use sectors as well as for material use, e.g., in industry. The marginal costs or willingness-to-pay for hydrogen-based options are derived from the alternative decarbonization options. Technology and economic analyses are made of the possible options in each application area. CAPEX and OPEX are taken into account within the entire lifetime of the plants. Unlike the sector models, hydrogen prices are not assumed, but an accepted price of the demand for hydrogen is calculated from the marginal costs. By comparing the results for Germany from the model-based method used in this working paper, the decisive parameters for calculating the demand function for hydrogen are identified and can be integrated into the long-term partial equilibrium model. Regional and country-specific parameters (e.g., energy prices) are adjusted accordingly when transferring the demand function.

5 Summary, Discussion and Conclusions

Hydrogen and its derivatives are important components to achieve climate policy goals, especially in terms of greenhouse gas neutrality. However, there is an ongoing controversial debate about the applications in which hydrogen and its derivatives should be used and to what extent. In addition to the ambitiousness of climate targets, a decisive criterion here is the price of hydrogen and its associated ability to compete with other options such as direct electrification.

To address this issue, this study aims at developing a methodological approach to determine the demand for hydrogen and its derivatives as a function of possible hydrogen price pathways and then applying it to Germany under the goal of Germany becoming greenhouse gas-neutral in 2045.

The price elasticity of hydrogen demand in the individual application areas of industry, transport and energy conversion is determined using techno-economic, agent-based simulation models or optimization models. These models map the alternative options for achieving the climate goals and evaluate these using economic criteria. For instance, whether it makes more sense economically to use electric cars or fuel cell cars depending on the hydrogen price pathways, which are defined exogenously. For certain areas - building heat and international air and maritime transport - the results of other studies are used rather than modeling.

One key result is that so-called no-regret applications are a very important driver of the demand for hydrogen. These are applications for which, based on current knowledge, there are hardly any other economically-attractive technology options available for achieving Germany's ambitious greenhouse gas reduction targets. The lack of alternatives means they are therefore price-inelastic to a large extent. These concern, in particular, the material and energy use of hydrogen in certain applications in industry (steel and basic chemicals). The calculations show that demand here will amount to 250 TWh in 2045, which is roughly 10% of the current final energy demand in Germany. Around 20 GW of electrolysis capacity would have to be installed in Germany alone just to meet German demand assuming that one third is produced domestically, which represents an enormous challenge. To put this in perspective: At the beginning of 2022, only 0.5 GW of electrolysis capacity was installed worldwide (IEA 2022). Developing hydrogen production is time-consuming and capital-intensive. Further, the need for a rapid rate of expansion is often emphasized if the set political targets to develop a hydrogen economy are to be reached (see Hydrogen Council (2021), Hydrogen Council (2022), IEA (2021b)).

International air and maritime transport also show high, price-inelastic demand for synthetic fuels to reduce greenhouse gases (209 TWh in 2045). In this study, it is assumed that this demand is covered by biogenic sources.

Because demand in these sectors is primarily for hydrogen and biogenic synthesis products, the implication is that cost-favorable hydrogen is not likely to be available in other sectors. Especially in other transport applications (cars, trucks, buses, rail and national aviation and shipping), for which direct electrification is often an alternative, the calculations show that hydrogen will only be used on a larger scale if it is available at a very low price. This is only the

case at wholesale hydrogen prices of less than 90 Euro/MWh in 2045, or even significantly lower, depending on the application. This also applies to the use of hydrogen for energy in industry to generate steam and heat, and even more so for the sector of building heat. At a price of 50 Euro/MWh, the analyses yield a total demand for hydrogen of 476 TWh in 2045.

However, price levels below 90 Euro/MWh and even lower are hardly to be expected. Even pure cost considerations show that this only seems feasible at present at very favorable locations around the world. Transport costs, profit margins, capital costs reflecting country risks, distribution costs, R&D costs etc. still have to be added to the production costs shown in these studies. Furthermore, the production quantities at very favorable locations are limited and, based on the information currently available, will not be sufficient to meet the emerging global demand. This means having to resort to sites with higher production costs as well. Based on current knowledge, it can be assumed that market prices for hydrogen in 2045 will be significantly above 90 Euro/MWh.

It does not seem reasonable, therefore, to pursue larger-scale support of hydrogen use in the sectors of building heat, land-based transport or energy use in industry. There may be exceptions to this in certain niche applications. For example, providing building heat if there is already hydrogen demand at a nearby industrial site.

In the energy conversion sector, there is an interesting wholesale price range (from 130 to 90 Euro/MWh), in which the demand for hydrogen is relatively price-elastic. This is related to the fact that options to balance supply and demand are necessary for the targeted expansion of renewable energies. Here, the options of using hydrogen storage and reconversion into electricity compete, among others, with options to increase the flexibility of demand. The flexibility options here include heat pumps, heat networks or electric vehicles. In addition, there is the option to use other storage options or to deploy even more renewables and accept the risk of their greater curtailment. In future, the prices for hydrogen will co-determine the extent to which it is used in the future.

The results for 2030 show that hydrogen demand will not yet be very high at this time (slightly more than 40 TWh). This hydrogen demand will be dominated by specific industrial applications. Support should focus on these in the coming years. Demand in 2030 only increases significantly if very low wholesale prices are assumed, which does not seem very realistic at present.

References

AGEB (2022): Bilanz 2020, Arbeitsgemeinschaft Energiebilanzen (AGEB): available at: https://ag-energiebilanzen.de/daten-und-fakten/bilanzen-1990-bis-2020/?wpv-jahresbereich-bilanz=2011-2020, last checked on 23.8.2022.

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

Brändle, G.; Schönfisch, M.; Schulte, S. (2021): Estimating long-term global supply costs for low-carbon hydrogen. In: Applied Energy 302 (2021) 117481. https://doi.org/10.1016/j.apenergy.2021.117481.

Bundesregierung (2020): Die Nationale Wasserstoffstrategie. Berlin: Bundesministerium für Wirtschaft und Energie (BMWi) (ed.). Available online at https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/die-nationale-wasserstoffstrategie.pdf?__blob=publicationFile&v=16, last checked on 12.11.2020.

Deutsch, M.; Maier, U.; Perner, J.; Unteutsch, M.; Lövenich, A. (2018): Die zukünftigen Kosten strombasierter synthetischer Brennstoffe. Ed. by Agora Verkehrswende, Agora Energiewende und Frontier Economics: Berlin, Köln.

European Commission (2020): A hydrogen strategy for a climate-neutral Europe, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brüssel: European Commission.

Fleiter, T.; Rehfeldt, M.; Herbst, A.; Elsland, R.; Klingler, A.L.; Manz, P.; Eidelloth, S. (2018): A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model. In: Energy Strategy Review, Volume 22, pp. 237-254.

Forschungszentrum Jülich (ed.) (2021): H_2Atlas-Africa. Available online at https://www.h2atlas.de/en/, last updated 13.11.2022, last checked 13.11.2022.

Fraunhofer ISI, Consentec, ifeu, Technische Universität Berlin (2022): Langfristszenarien. Website download: https://langfristszenarien.de/enertile-explorer-de/index.php.

Fraunhofer ISI (2023): Aladin Modell zur Simulation der Marktdiffusion alternativer Antriebe im Verkehr. Available online at https://www.aladin-model.eu/, last updated on 13.01.2023, last checked on 13.01.2023.

Frontier (2021): Power to Gas, Missing Money und der Wärmesektor als wichtiger „Heimatmarkt" beim Markthochlauf in Deutschland – Ein Diskussionsbeitrag zur Nationalen Wasserstoffstrategie („NWS"). Frontier economics.

Gnann, T.; Plötz, P.; Kühn, A.; Wietschel, M. (2015): Modelling Market Diffusion of Electric Vehicles with Real World Driving Data – German market and Policy options. In: Transportation Research Part A, Vol. 77, July 2015, pp. 95-112.

Gnann, T.; Speth, D.; Krail, M..; Wietschel, M. (2022): Langfristszenarien für die Transformation des Energiesystems in Deutschland (Langfristszenarien 3, T45-Sznarien) – Modul Verkehr. Studie im Auftrag des BMWi.

Hank, C.; Sternberg, A.; Köppel, N.; Holst, M.; Smolinka, T.; Schaadt, A.; Henning, H.-M. (2020): Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. Retrieved from 10.1039/d0se00067a.

Hampp,J.; Düren, M.; Brown, T. (2021): Import Options for Chemical Energy Carriers from Renewable Sources to Germany. ArXiv:2107.01092 [Physics], July. http://arxiv.org/abs/2107.01092.

Heuser, P.-M. et al. (2019): Techno-economic analysis of a potential energytrading link between Patagonia and Japan based on CO_2-free hydrogen. In: International Journal of Hydrogen Eenergy 44 (2019) 12733e12747.

Hobohm, J.; auf der Maur, A.; Dambeck, H.; Kemmler, A.; Koziel S.; Krei-Delmeyer, S. et al. (2018): Status und Perspektiven flüssiger Energieträger in der Energiewende. Eine Studie der Prognos AG, des Fraunhofer-Instituts für Umwelt-, Sicherheits- und Energietechnik UMSICHT und des Deutschen

Biomasseforschungszentrums DBFZ. Endbericht. Prognos AG; Fraunhofer-Institut für Umwelt-, sicherheit- und Energietechnik (UMSICHT); Deutsches Biomasseforschungszentrum: Berlin.

Hydrogen Council (2020): Path to hydrogen competitiveness - A cost perspective. Hydrogen Council.

Hydrogen Council (2021): Hydrogen Insights – A perspective on hydrogen investment, market development and cost competitiveness. Hydrogen Council.

Hydrogen Council (2022): Hydrogen Insights 2022 – An updated perspective on hydrogen market development and actions required to unlock hydrogen at scale. Hydrogen Council and McKinsey & Company.

Hydrogen Council & McKinsey (2022): Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization. Hydrogen Council.

IEA (2021a): World Energy Outlook 2021. Available online at https://www.iea.org/reports/world-energy-outlook-2021, last checked on 15.11.2022.

IEA (2021b): Global Hydrogen Review 2021. International Energy Agency: Available online at https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf, last checked on 05.10.2021.

IEA (2022): Electrolysers - Technology deep dive. https://www.iea.org/reports/electrolysers, last checked on 23.1.2023.

IRENA (2022): Global Hydrogen Trade to Meet the 1.5°C Climate Goal – Part I. International Renewable Energy Agency. Abu Dhabi: IRENA.

JRC (2019): Hydrogen use in EU decarbonisation scenarios. Joint Research Centre.

Knosala, K.; Langenberg, L.; Pflugradt, N.; Stenzel, P.; Kotzur, L.; Stolten, D. (20022): The role of hydrogen in German residential buildings. In: Energy & Builidngs 276 (2022) 112480.

Lux, B.; Pfluger, B. (2020): A supply curve of electricity-based hydrogen in a decarbonized European energy system in 2050. Applied Energy, 269, 115011. Permalink: https://doi.org/10.1016/j.apenergy.2020.115011.

Lux, B.; Gegenheimer, J.; Franke, K.; Sensfuß, F.; Pfluger, B. (2021): Supply curves of electricity-based gaseous fuels in the MENA region. In: Computers & Industrial Engineering, S. 107647. DOI: 10.1016/j.cie.2021.107647.

Monopolkommission (2021): Energie 2021: Wettbewerbschancen bei Strombörsen, E-Ladesäulen und Wasserstoff nutzen. 8. Sektorgutachten der Monopolkommission gemäß § 62 EnWG 2021.

NREL (2021): The Technical and Economic Potential of the H2@Scale Concept within the United States. National Renewable Energy Laboratory. Retrieved November 8, 2021, from https://www.oeko.de/fileadmin/oekodoc/Die-Wasserstoffstrategie-2-0-fuer-DE.pdf, last checked on 23.1.2023.

Pfennig, M.; Gerhardt, N.; Pape, C.; Böttger, D. (2017): Mittel- und langfristige Potenziale von PtL- und H_2-Importen aus internationalen Vorzugsregionen. Teilbericht im Rahmen des Projekts: Klimawirksamkeit Elektromobilität – Entwicklungsoptionen des Straßenverkehrs unter Berücksichtigung der Rückkopplung des Energieversorgungssystems in Hinblick auf mittel- und langfristige Klimaziele. Teilbericht. Bremerhaven: Fraunhofer-Institut für Windenergie und Energiesystemtechnik IWES.

Pfennig, M.; von Bonin, M.; Gerhardt, N. (2021): PTX-Atlas - Weltweite Potenziale für die Erzeugung von grünem Wassrstoff und kliamneutralen synthetsichen Kraft- und Brennstoffen. Teilbericht im Rahmen des Projektes: DeV-KopSys. Kassel: Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik IEE.

Plötz, P; Gnann, T.; Wietschel, M. (2014): Modelling market diffusion of electric vehicles with real world driving data – Part I: Model structure and validation Elsevier. In: Ecological Economics Vol 107, Nov. 2014, pages 411-42.

Prognos (2020): Kosten und Transformationspfade für strombasierte Energieträger. Endbericht zum Projekt „Transformationspfade und regulatorischer-Rahmen für synthetische Brennstoffe". Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie.

Quarton, C. J.; Tlili, O.; Welder, L.; Mansilla, C.; Blanco, H.; Heinrichs, H.; Leaver, J.; Samsatli, N. J.; Lucchese, P.; Robinius, M.; Samsatli, S. (2020): The curious case of the conflicting roles of hydrogen in global energy scenarios. In: Sustainable Energy & Fuels, 4 (1), pp. 80-95.

Repenning et al. (2021): Projektionsbericht 2021 für Deutschland. Gemäß Artikel 18 der Verordnung (EU) 2018/1999 des Europäischen Parlaments und des Rates vom 11. Dezember 2018 über das Governance-System für die Energieunion und für den Klimaschutz, zur Änderung der Verordnungen (EG) Nr. 663/2009 und (EG) Nr. 715/2009 des Europäischen Parlaments und des Rates sowie §10 (2) des Bundes-Klimaschutzgesetzes. Öko-Institut, Fraunhofer ISI, IREES. https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/projektionsbericht_2021_bf.pdf.

Riemer, M.; Zheng, L.; Pieton, N.; Eckstein, J.; Kunze, R.; Wietschel, M. (2022): Future hydrogen demand: A cross-sectoral, multiregional meta-analysis. HYPAT Working Paper 04/2022. Karlsruhe: Fraunhofer ISI (ed.).

Riera, J.; Barner, L.; Holz, F.; Rathje, L.; Sogalla, R.; Hirschhausen, C. (2021): The global hydrogen market 2050 – A model-based comparison of pathways and policy constraints. IAEE Proceedings. Available online at: http://www.iaee.org/proceedings/article/17189, last checked on 13.1.2023.

Schönfisch, M. (2022): Charting the Development of a Global Market for Low-Carbon Hydrogen. EWI Working Paper No 22/03.

Sensfuß, F. et al. (2021): Langfristszenarien für die Transformation des Energiesystems in Deutschland - Treibhausgasneutrale Szenarien; Kurzzusammenfassung. Available online at https://langfristszenarien.de/enertile-explorer-wAssets/docs/LFS3_Executive_Summary_2021_05_19_v19.pdf, last checked on 23.1.2023.

SRU (2021): Wasserstoff im Klimaschutz. Klasse statt Masse. Stellungnahme.

Timmerberg, S.; Kaltschmitt, M. (2019): Hydrogen from renewables: Supply from North Africa to Central Europe as blend in existing pipelines – Potentials and costs. In: Sustainable Energy 237 (2019), pp. 798-809.

Thomsen, J.; Fuchs, N.; Meyer R.; Wanapinit, N.; Ulffers, J.; Bavia Bampi, B.; Lohmeier, D.; Prade, E.; Gorbach, G.; Sanina, N.; Engelmann, P.; Herkel, S.; Kost, C.; Braun, M.; Lenz, M. (2022): Bottom-Up Studie zu Pfadoptionen einer effizienten und sozialverträglichen Dekarbonisierung des Wärmesektors. Studie im Auftrag des Nationalen Wasserstoffrats. Freiburg, Kassel: Fraunhofer ISE, Fraunhofer IEE (ed.)

Ueckerdt, F.; Bauer, C.; Dirnaichner, A. et al. (2021): Potential and risks of hydrogen-based e-fuels in climate change mitigation. In: Nat. Clim. Chang. 11, 384–393 (2021). https://doi.org/10.1038/s41558-021-01032-7.

Umweltbundesamt (2022a): Treibhausgasemissionen stiegen 2021 um 4,5 Porzent. Pressemitteilung des Umweltbundesamtes. Internet Download https://www.umweltbundesamt.de/presse/pressemitteilungen/treibhausgasemissionen-stiegen-2021-um-45-prozent, last checked on 23.1.2023.

Wietschel, M.; Zheng, L.; Arens, M.; Hebling, C.; Ranzmeyer, O.; Schaadt, A.; Hank, C.; Sternberg, A.; Herkel, S.; Kost, C.; Ragwitz, M.; Herrmann, U.; Pfluger, B. (2021a): Metastudie Wasserstoff – Auswertung von Energiesystemstudien. Studie im Auftrag des Nationalen Wasserstoffrats. Karlsruhe, Freiburg, Cottbus: Fraunhofer ISI, Fraunhofer ISE, Fraunhofer IEG.

Wietschel, M., Eckstein, J.; Riemer, M.; Zheng, L.; Lux, B: Neuner, F.; Breitschopf, B.; Pieton, N.; Nolden, C.; Pfluger, B.; Thiel, Z.; Löschel, A. (2021b): Import von Wasserstoff und Wasserstoffderivaten: von Kosten zu Preisen. HYPAT Working Paper 01/2021. Karlsruhe: Fraunhofer ISI (ed.)

World Energy Council (2021): Hydrogen Demand and Cost Dynamics. Working Paper.

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Appendix A

The following tables depict the competition in the individual subsectors based on the competitive situation. It should be pointed out that the tables only provide a general overview, the technological resolution in the models is much more detailed.

Table 1: Technology competition in industry and the tertiary sector (trade, commerce and services)

Application area	Technology up to now	Direct electrification options	Hydrogen/synthesis technologies	Other renewable energy sources
Industry				
Industrial process heat	Gas boiler Steam	Electrode boiler Induction heating Plasma process Resistance heating Heat pumps	Synthetic fuels Hydrogen	Biomass/biogas
Steel (primary route)	Oxygen steel/Blast furnace route (coke, coal, fossil gases)	Only process heat	Direction reduction using hydrogen/synthesis gas + electric arc furnace	Biomass/biogas
Chemicals	Basic chemicals based on oil and natural gas	Only process heat	Synthetic basic materials	Biomass/biogas
Ammonia	Produced using natural gas	Only process heat	Hydrogen (hydrocarbons possible)	Biomass/biogas
Low-temperature heat for households, industry, tertiary sector				
Low-temperature heat	Oil, gas, district heating	Heat pumps, resistance heating	Synthetic gas substitutes natural gas	Biomass/biogas

Source: own representation

Table 2: Technology competition in the transport sector

Application area	Technology up to now	Direct electrification options	Hydrogen/synthesis technologies	Other renewable energy sources
Transport				
Passenger cars	Cars with internal combustion engines powered by gasoline, diesel, gas	Battery-electric cars	Fuel cell vehicles Synthetic fuels	Biofuels
Light-duty delivery trucks	Vehicles with internal combustion engines powered by gasoline, diesel, gas	Battery-electric trucks	Fuel cell vehicles Synthetic fuels	Biodiesel, purified biogas
Heavy-duty road freight trucks	Diesel engines Gas-powered vehicles	Overhead lines on highways for battery-electric catenary trucks	Fuel cell vehicles Synthetic fuels	Biodiesel, purified biogas
Rail	Electric motor Diesel motor	Electrification of non-electrified tracks	Fuel cell-powered Battery-powered Synthetic fuels	Biodiesel
Air transport, European	Turbines (kerosene)	Battery-powered (limited)	Fuel cell-powered Synthetic kerosene	Bio-based kerosene
Air transport, Continental	Turbines (kerosene)	No foreseeable technologies	Synthetic kerosene	Bio-based kerosene
Shipping, European	Ship engines (heavy fuel oil, diesel), in future more LNG	Battery-powered (limited)	Fuel cell-powered Synthetic diesel, synthetic LNG	Biodiesel, purified biogas
Shipping, international	Ship engines (heavy fuel oil, diesel), in future more fossil LNG	No foreseeable technologies	Synthetic diesel, synthetic LNG	Biodiesel, purified biogas

Source: own representation

Table 3: Technology competition in the conversion sector

Application	Technology up to now	Direct electrification options	Hydrogen/synthesis technologies	Other renewable energy sources
Electricity supply				
Short-term stabilization of power grid, provision of flexibility	Flexible use of power stations Demand Side Management DSM)/ Demand Side Response (DSR) Making demand more flexible Grid expansion	Electricity storage (pumped storage, batteries ...)	Flexible operation of electrolysis	Flexible electricity generation from biomass
Stabilization of power grid due to structural lack of renewable generation (e.g. dark doldrums)	Flexible use of power stations Demand Side Management (DSM)/ Demand Side Response (DSR) Conventional storage systems	No foreseeable technologies	Synthetic gas for reconversion into electricity in power stations or Fuel cells Hydrogen storage Synthesis gas storage	Flexible electricity generation from biomass
Other conversion sector				
Refineries	Fossil-based hydrogen (mainly natural gas) for, e.g., desulfurization or hydrocracking	Only process heat (complex internal energy flows)	Green hydrogen replaces fossil hydrogen	Biomass/biogas

Source: own representation

The investments and the running costs of using hydrogen and of the alternative option determine whether hydrogen is used. The willingness-to-pay for hydrogen is derived from this. In this context, it is helpful to divide the subsectors into three groups depending on their flexibility for using hydrogen alternatives. These groups are described in more detail below (a similar approach is taken in Wietschel et al. (2021a), Agora Energiewende 2021). These groups will also play a role in assigning prices and when considering the development over time.

- No regret: In the "no-regret" group, demand for hydrogen is driven by the lack of alternative decarbonization measures. Direct electrification is only possible to a limited extent or not at all, which is why the only alternatives to hydrogen are the use of fossil fuels with carbon capture and storage (CCS) or biomass. The limited alternatives mean that demand is likely to be quite inelastic and consumers cannot react responsively to changes in the price of hydrogen. This group features industrial applications that are already the main demand sectors for hydrogen today, such as ammonia and basic chemicals, supplemented in the future by steel. In addition, international air transport and shipping.
- No lock-in: The "no lock-in" group contains applications where decarbonization can be realized by both the direct use of renewable electricity and renewable hydrogen and it is not yet clear which alternative will be the most economical. These include, for example,

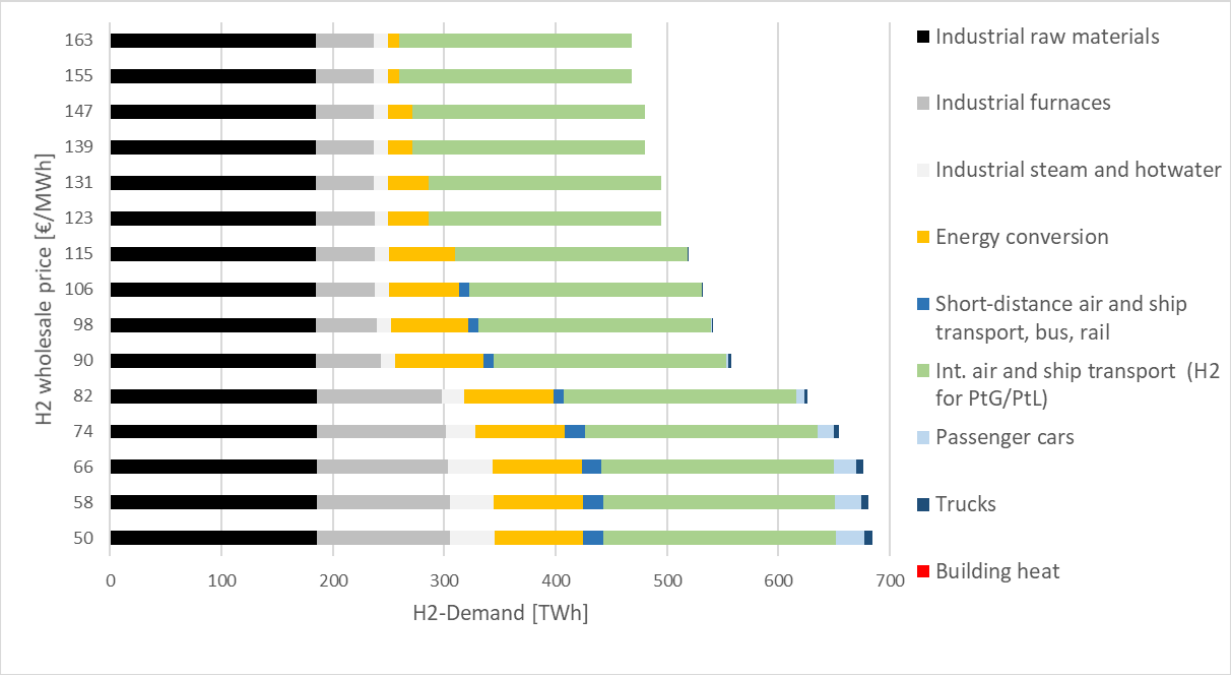
high-temperature heat in industry or heavy-duty transport. Demand is elastic and consumers are responsive to changes in the price of hydrogen.

- Game-changing: In the "game-changing" group, which includes passenger transport and space heating, using electricity directly is the more efficient decarbonization measure. There may be other factors that favor hydrogen and its derivatives such as available infrastructures or acceptance as well as plummeting production costs for hydrogen. In this group, demand is quite elastic and buyers are responsive to changes in the price of hydrogen.

Appendix B

The following depicts the demand for synthesis products in 2045:

Figure 8: Price-dependent demand for synthesis products (hydrogen and biogenic) in Germany in 2045 under the target of greenhouse gas neutrality



Source: own representation