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On Bremen's Industrial Transformation: The Role of Hydrogen in Production

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Abstract

Hydrogen serves as an energy source and represents an important cornerstone for achieving the goal of maintaining a level of zero-carbon-dioxide emissions in industry production processes. Our analysis is based on the computable general equilibrium framework and focuses on a partial switch to hydrogen used in production in northern Germany, particularly in the Bremen region. The simulation results indicate that Bremen's chemical, steel, and copper industries could replace up to 1.5, 15, and 35%, respectively, of petroleum and natural gas with hydrogen, without negative effects on overall production, until 2032. The share of electricity based on renewable sources in the production of hydrogen amounts to approximately 74%. This step can be seen as required for the production of green hydrogen, i.e., in the absence of fossil energy sources.

Keywords: Computable General Equilibrium Model Analysis, Hydrogen Economy, Regional and Industrial Development, Bremen.

JEL classification: C68, O13, Q21, R13

1 Introduction

The replacement of fossil energy sources with alternative energy sources, especially in industry, aiming to significantly reduce climate-damaging carbon dioxide (CO_2) emissions, is becoming increasingly relevant in the public discussion. The *iron* and *steel* industry, which is responsible for one-third of global industrial CO_2 emissions, is facing significant pressure to transition to more sustainable methods of production—steel is widely utilized in every nation and across nearly all industries and experiencing growing demand worldwide (Lopez, Farfan, and Breyer 2022). Particular importance is attached to the chemical raw material hydrogen (H_2) and its role as an input factor. H_2 is produced through the process of electrolysis, i.e., by splitting water into H_2 and oxygen, and is considered particularly sustainable in terms of reducing CO_2 emissions. The German federal government's National Hydrogen Strategy 2020 provides, among other things, for the development of a H_2 infrastructure in the form of a core network. In addition, applications in industry and the transport sector should be promoted (BMWK 2020). Moreover, the European Commission considers H_2 an important pillar of the planned European Green Deal (EuropeanCommission 2020). The key advantage of H_2 usage is that it produces no emissions when used in fuel cells and is generated from renewable energy sources. Additionally, H_2 can be stored and transported, making it versatile for use in a wide range of applications (Bolz, Thiele, and Wendler 2024). In addition to reducing CO_2 emissions, the federal German government hopes to provide a positive stimulus for economic development in the medium to long term (BMWK 2020).

This paper is developed within the context of the Hydrogen for Bremen's Industrial Transformation (hyBit) project, which aims to decarbonize Bremen's key industries by integrating H_2 technologies. As part of the broader effort to support the European Green Deal and Germany's climate goals, this project focuses on developing H_2-based energy systems, mainly for the *steel* industry, which is traditionally reliant on fossil fuels. In doing so, hyBit not only explores the potential of H_2 to replace

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conventional energy sources but also paves the way for the large-scale industrial adoption of green H_2. This initiative is key to fostering sustainability and advancing the decarbonization of energy-intensive industries. In this context, steel producer ArcelorMittal announced plans to achieve by 2030, where the Bremen and Eisenhüttenstadt sites could produce up to 3.8 million tonnes of green (flat-bar) steel using direct reduction facilities (DRFs) and electric arc furnaces (EAFs), resulting in significant reductions in CO_2 emissions. This technology shift will require investments estimated between 1.5 and 3 billion euro (ArcelorMittal 2021, Die Senatorin für Wirtschaft and Finanzen 2024).

We consider a microfounded macroeconomic model that depicts the regional and industrial effects of various disturbances in line with the overarching story of establishing a H_2 economy in northern Germany. With the main focus being on investigating the development in the federal state of Bremen (Bremerhaven) via a computable general equilibrium (CGE) model, we also consider the remaining federal states of Schleswig-Holstein, Hamburg, Mecklenburg–Western Pomerania, and Lower Saxony as well as the rest of Germany (RoDE) and shed light on the impact of supply and demand shocks on selected industries until 2032. Therefore, in this study, we allow for i) the buildup of a (green) H_2 industry via investment and technology shocks in almost all northern German states and ii) a partial switch in Bremen's heavy industry away from fossil-based energy and toward H_2- and electricity-based renewable sources used in production until 2032.

The remainder of this paper is structured as follows. In Section 2, we provide a review of the literature linked to our study. The CGE methodology employed in this study is described in Section 3. In Section 4, we specify the shock scenario, and highlight the main features important to our analysis. A discussion of the results obtained from the simulation is provided in Section 5. Section 6 concludes the paper. Finally, the computational steps and additional material are relegated to the Appendix.

2 Literature Review

Owing to the nature of the subject matter, macroeconomic studies incorporating H_2 as an input in production are rather scarce. To our knowledge, we are among the first to investigate the effects of establishing a H_2 industry at the regional level for Germany via a CGE model analysis. Mueller and Gronau 2023 note that there are no explicit H_2-related CGE studies at the country level for Germany prior to 2024; the interested reader is referred to their survey article, where they provide a detailed overview of the recent CGE literature related to H_2. For a more general review of the applications of regional CGE models, we refer to Ghaith *et al.* 2021.

In the run up to this paper, Sacht 2024 focuses solely on the impact of supply shocks on the output and price development in the H_2 sector in northern Germany. His CGE simulation results indicate a decrease in the industry price for H_2 by 17–35% across northern states and, hence, a potential narrowing of the existing price gap for H_2 versus fossil fuel after 2030. In the companion paper to this one by Lagemann and Sacht, forthcoming, the authors investigate the impact of supply shocks together with an up to 100% switch in production toward H_2 for selected industries in all northern states until 2045. The above authors show that the vast majority of heavy industries may suffer from high initial H_2-fossil fuel price caps in terms of negative output development, which they cannot overcome, in all regions. The opposite may be possible in the case of an additional cutback in the number of regulatory measures such as bureaucratic requirements. This situation is synonymous with an increase in the trade efficiency of H_2 shipped between regions and, therefore, can reduce the corresponding delivery price, which has a positive effect on industry production and overall regional macroeconomic performance.

Few studies involving CGE analysis that focus on steel production exist. Mayer, Bachner, and Steininger 2019 report the results from their simulation study based on a CGE model for Europe with 16 sectors and 17 regional aggregates at the national level. With a focus on establishing process-emission-free iron and steel technologies in production, the above authors find that a switch to H_2-based production is not competitive with a switch based on fossil fuel until 2035, without an accompanying strong decrease in electricity costs. Ren *et al.* 2021 discuss the decarbonization of the *iron* and *steel* industry on the basis of a CGE model for China to meet the country's target to achieve carbon neutrality by 2060. The above authors claim that a H_2-based switch of 23–25% in the production process should be implemented by 2050 to meet China's carbon oxide mitigation target.

Another study of Germany by Schumacher and Sands 2007 focuses on a CGE analysis of steel production as part of energy-intensive industries. The above authors demonstrate that the interaction between energy and nonenergy markets can be effectively analyzed through CGE simulations, which respond to price changes driven by policy interventions. Schumacher and Sands 2007 explicitly consider the choice of production technology as either a conventional or EAF choice. Their CGE model allows for shifts in energy consumption in response to changes in energy or CO_2 prices such as those of the EU Emissions Trading System. This approach captures shifts between technologies, which is crucial because, ultimately, transformation in energy-intensive industries occurs through price mechanisms, making it a question of location policy. However, with the focus being only on Germany as an aggregate, the above study lacks regional differentiation and the presence of a H_2 market.

Some papers address the need for proper infrastructure and the cost development related to H_2 production. Via CGE analysis, Espegren *et al.* 2021 investigate the development of a large-scale H_2 economy in Norway. Focusing primarily on heavy-duty transport, the authors emphasize the need to establish a H_2 infrastructure, such as refueling and charging stations until 2050. In an earlier study by Lee 2012, a single-country CGE model for Taiwan is considered to compare the costs of different types of energy sources used to produce H_2, showing that renewable energy sources such as wind and photovoltaic energy will become more cost-competitive than will nuclear energy until 2040.

3 The CGE Methodology

In this study, simulations are carried out via a specific version of a CGE model, which allows for a model-based evaluation of macroeconomic developments, i.e., integral dependencies between economic variables such as gross domestic product (GDP) and aggregate employment. A CGE model serves as an analysis tool that links a mathematical system of equations to empirical observables given in levels on the basis of economic assumptions. These observables are expressed as the product of the quantity times the price for each commodity for a designated (base) year.

A bottom-up CGE model depicts the bidirectional relationships between supply and demand in the economy. At its core, such a model follows the neoclassical paradigm whereby markets operate without disturbances under perfect competition, which implies that after all adjustments have occurred, markets are in equilibrium, where supply equals demand. Changes in the model variables are described on the basis of the corresponding microfounded (typically) nonlinear equations, which are linearized by applying a total differential approach.[1] Despite the existing approximation

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[1] For illustration purposes, let us consider the following example. Given a function, $Y = X^3$, the corresponding steady-state expression is $Y_0 = X_0^3$, where subscript 0 (1) denotes the initial (final) equilibrium values for the variables X and Y

error relative to a nonlinear representation, a linearized model exhibits a closed reduced form solution and, hence, becomes much more manageable mathematically than does a nonlinearized model.

Microfoundation implies that agents' decision-making process stems from determining the optimal outcome of their objective function conditional on available resources. For example, each industry in the economy minimizes the costs of producing its output by selecting sufficient inputs, that is, labor, capital, and intermediate products. An industry's investment schedule depends on the movement in its rates of return on capital. All industries are price takers due to the assumption of perfect market competition. Therefore, these types of cost-increasing industries operate until the 'zero-profit condition' is met, which implies that in the case of a decrease in input costs (e.g., a drop in the real wage), industries demand more of the specific input(s) for use in the production process until all costs at the margin are covered entirely by the market price for the industry's output. The latter is chosen to satisfy demand, which is driven by prices and income. According to neoclassical theory, households follow a linear expenditure system of demand subject to a budget constraint (Wittwer 2022).[2]

We consider the enormous regional model (TERM) developed by the Centre of Policy Studies (COPS) at Victoria University Melbourne, Australia, for our analysis (Horridge, Madden, and Wittwer 2005). In particular, a version tailored exclusively to the wider European area, e.g., including Ukraine, called EuroTERM, is used. In general, TERM builds on a multiregional approach, where every region resembles its own economy. Statistical information about each individual region is given at the second Nomenclature of Territorial Units for Statistics (NUTS2) level. In the case of EuroTERM, the model can generally address up to 328 NUTS2 regions belonging to 40 countries in total. In addition, a maximum of 74 industries are identifiable. This approach allows us to study the impacts of region-specific shocks, as regional shares are applied to national input–output tables. This type of data is available from Eurostat and the Global Trade Analysis Project (GTAP), where the latter collects and provides empirical observations on bilateral trade patterns. Owing to the operating expense of setting up an enormous number of entries stored in input–output tables, databases become infrequently updated. In our case, the final database contains information available for 2017 and is provided by COPS together with the numerical specification for the model parameters. Detailed information on the selection and linkage of the data to TERM, in general, is provided by Horridge 2011 and, more specifically, for EuroTERM, by Wittwer 2022.[3]

On the basis of the database described, both supply- and demand-related developments that affect the economic structure in one or more regions can be simulated. A detailed representation of the

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before (after) the simulation is conducted. Applying the total differential leads to $\mathrm{d}Y = 3 \cdot X_0^2 \cdot \mathrm{d}X$ with $\mathrm{d}Y = Y_1 - Y_0$ and $\mathrm{d}X = X_1 - X_0$. By multiplying the left (right) side by Y_0/Y_0 (X_0/X_0) and defining $y = \mathrm{d}Y/Y_0$ and $x = \mathrm{d}X/X_0$, i.e., the percentage change in both variables and finally taking the steady-state expression into account, we arrive at the linearized equation given by $y = 3 \cdot x$. Hence, a variable with small letters denotes the percentage deviation of that variable from its base value.

[2] It becomes obvious that feedback effects can occur as prices adjust in response to disturbances in the economy, such as a technology shock. For example, in the state of temporary disequilibrium in the labor market (i.e., either an excess supply of or an excess demand for labor), a change in the real wage will occur to restore the final equilibrium. As a result, real wage adjustments affect industries' cost structure as the price for input labor changes. This effect is more pronounced when more labor is intensively used in the production process across industries and so on.

[3] To run simulations, the user is required to extend the core structure of the model and specify the magnitude of the shocks. In addition, the closure conditions of the model to ensure consistency regarding the equal match of all endogenous variables to the corresponding equations must be set. The user is also obligated to check if the model outcome in terms of (updated) databases is balanced, i.e., that no significant numerical disequilibrium states occur. However, an in-depth discussion of these topics is beyond the scope of this paper. Therefore, we refer to Burfisher 2016 for a more general introduction to the CGE methodology. The results reported here are obtained using GEMPACK, version 12.1.004 (Horridge *et al.* 2018).

supply relationship between industries or sectors in the regions then allows for (in)direct repercussions due to changes in the value chain to be estimated. This situation creates a differentiated picture of the expected effects. A link with regional employment data at the industry level, for example, ultimately makes deriving effects on the structure of labor demand possible. With this in mind, we shed light primarily on the interactions between 8 subregions that form the northern part of Germany. These regions are (with the NUTS2 code in parentheses) Schleswig–Holstein (DEF0), Bremen (together with Bremerhaven; DE50), Hamburg (DE60), Mecklenburg–Western Pomerania (DE80) and Lower Saxony (comprising DE91 to DE94). In addition, we obtain data for the RoDE, the rest of Europe (RoE), the US and China. However, we refrain from reporting results for all regions other than those in northern Germany since the impact of subregion-specific shocks on the large economic regions of the RoDE, the RoE, the US, and China, together with the occurrence of potential feedback effects discussed in this study, are negligible.

For a clear arrangement and better manageability, in our version of EuroTERM, we consider only 33 out of 74 industries in our simulations. The focus is on the so-called heavy industries—*chemical*, *steel* and *copper*—as well as *renewable electricity* and H_2. The latter is considered an embryo industry, i.e., a tiny industry with a low level of endowments regarding intermediate goods, primary factors, overall output, and so on. This holds since the H_2 industry is close to nonexistent at the beginning of our simulation. As the linearized model addresses percentage changes in the variables relative to their initial values, the latter cannot be zero. Therefore, arbitrarily small numbers for all expressions linked to H_2 in the 2017 database are set. This practice of parameterizing newly established industries is common in CGE modeling.

We conduct a comparative statics analysis, i.e., a comparison of the results obtained for the initial and final equilibrium states. In EuroTERM, these results are expressed through changes in the model variables in percentage terms relative to the base from one state to another state. We follow a long-run closure, as we address a 10-year period from 2022 until 2032. This type of closure reflects the assumption that capital is endogenously determined and that employment is exogenously given. The latter applies, however, only to the national aggregate of employment. Hence, for Germany as a whole, we observe changes in the real wage instead. In contrast, across the different German subregions (including the RoDE), employment alongside the real wage is endogenous, with a low degree of labor mobility. This is one of the key assumptions for modeling regional- and countrywide labor markets in EuroTERM (see Wittwer 2022). For all the results presented in this study, it is ensured that for subsequent simulations, the corresponding initial (2017/2022) and final (2032) databases are balanced; i.e., there are no significant numerical deviations in the supply from the demand schedules (or vice versa) to be observed.

4 Modeling Bremen’s partial transformation until 2032

By choosing suitable values for the model parameters, we account for specific conditions that apply to different markets. This type of parameterization is carried out transparently for the respective application under consideration of the regional economies’ structures expressed through input–output relationships. In the following, we refer to the industry producing electricity from wind and solar (photovoltaic) energy simply as *ElecRenew*, while we speak of the *hydrogen* and H_2 industries synonymously. We use the spot exchange rate between US dollars and euros (DEXUSEU), which takes a value of 1.1 as of June 1, 2024, to convert expressions given in million euros into foreign currency.

4.1 Shock Scenario

Improvement in Technology

We assume a 10% increase in the efficiency of inputs used in the production of *ElecRenew*, which holds uniformly across all regions. According to the concept of Hicks neutrality, this type of technology shock resembles a productivity gain to all inputs, which leads to fewer primary factors (labor and capital) and intermediate goods being required to produce the same unit of output. This situation implies a relaxation in the industry's cost structure where, as a result, the output level increases ceteris paribus, i.e., for a given price level.

We take some liberty regarding the assumption of the change in the degree of efficiency in the production of *ElecRenew* on the basis that in reality, we currently observe degrees of 45-50% (wind) and 14-20% (solar). With respect to the electrolysis process, however, we directly follow Maier 2018, as we assume a change in the degree of efficiency of H_2 production of 11%. The latter reflects a potential increase in the degree from 59 to 70% until 2030 in the power-to-gas approach to H_2. For information on how both types of shocks affect the model variables, particularly the final industry output, we refer to Appendix A.1.

Investment in Capital Stock

We utilize data on planned investment in the capital stock of the *ElecRenew* and H_2 industries until 2032. Information on investment in electricity from renewable energy sources is taken from the 2022 and 2023 reports published by the Federation-Länder Cooperation Committee, which provides an annual report on the state of expansion of renewables in Germany (Bund-Länder-Kooperationsausschuss 2022, 2023). In particular, the numbers of newly installed net capacities with respect to on- and offshore windmills plus solar panels in each region of northern Germany as well as the remaining country in 2021 and 2022 are considered. We then extrapolate these investment numbers ten years into the future until 2032; i.e., we pretend that every two years, the same amount of new capacity is built. Since the installed capacity is given in megawatts, considering 2,216 full load hours per year (Schlesinger *et al.* 2014), we arrive at all the entries expressed in megawatts per hour (mWh). These numbers are then multiplied by the 2021 price for electricity, which is 346.17 USD/mWh.[4] By expressing all the entries in million US dollars, the numbers are then ready for use in our simulations via EuroTERM and can be found in Table 1.[5]

Table 1. Investment in the H_2 and *ElecRenew* industries until 2032 (in million US dollars)

	DE50	DE60	DE80	DE91	DE92	DE93	DE94	DEF0	RoDE	Total
ElecRenew	56.77	81.70	3,780.72	1,756.30	1,756.30	1,756.30	1,756.30	4,241.37	50,354.05	60,270,89
H_2	554.03	127.03	1,040.97	–	–	–	–	10,061.34	–	11,783.37

Note: The following assignments apply. DE50 = Bremen (Bremerhaven), DE60 = Hamburg, DE80 = Mecklenburg–Western Pomerania, DE91 = Braunschweig, DE92 = Hannover, DE93 = Lueneburg, DE94 = Weser Ems, DEF0 = Schleswig–Holstein, and RoDE = rest of Germany.

Information on investment in electrolysis capacity given in megawatts is available only for the Bremen (Bremerhaven), Hamburg, Mecklenburg–Western Pomerania, and Schleswig–Holstein regions. Publicly available data on planned investment projects by a plethora of firms in these regions have been researched online. We convert all the numbers to mWh under consideration

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[4] The corresponding number is taken from strom-report.de (accessed on March 18 2024).

[5] Note that information on newly installed capacity in *ElecRenew* is available only for the entire federal state of Lower Saxony but not for its corresponding NUTS2 subregions DE91 to DE94. For simplicity, we take a symmetric approach and distribute the total amount of the state's investment given by 7,025.20 million US dollars equally across all subregions.

of 4,000 full load hours per year, as stated by Doucet *et al.* 2023. The above authors argue that the 2023 price for (green) H_2 amounts to 0.179 USD/kWh (US dollars per kilowatt hour). This value is based on the 'Hydex' price index published by E-Bridge Consulting.[6] The index resembles the marginal costs for producing H_2, excluding the margin costs related to transport and shipping.[7] Converting the price into USD/mWh and multiplying it by the product of investment numbers and full load hours, we can obtain the corresponding entries displayed in the last row of Table 1. All of those entries are then used to compute the percentage change in the capital stock in all regions until 2032. Further information is provided in Appendix A.2.

Partial Switching in Production

Fossil fuel, as an input factor in production, consists of petroleum, coal, and natural gas. In the following, we summarize these types of energy sources into the commodity *PetroCoalPrd*. Since we address the value of commodities expressed in units of currency, switching from *PetroCoalPrd* to H_2 in production poses no problem as long as the prices of both commodities do not differ. In reality, however, there exists a gap between the price for *PetroCoalPrd* and that for H_2, which is not surprising since, at the beginning of our simulations in 2022, the supply of H_2 was scarce. This situation implies that any switch in the production process away from fossil fuel and toward H_2 places a financial burden on industries (at least at the beginning of the simulation) as their cost structure tightens.

To compute the price gap, we consider the price for H_2 relative to that for fossil fuel. With respect to the latter, we follow Doucet *et al.* 2023 and consider the average price for natural gas in 2023, which is 0.076 USD/kWh. Furthermore, we once again consider their declaration for the 2023 H_2 price of 0.179 USD/kWh. The corresponding price gap is then given by the (rounded) value of 2.33; i.e., H_2 is initially 2.33 times more expensive than is natural gas. Hence, when facing a positive price gap, industries must overcome this liability regarding the input cost for H_2 when switching.

Although it is possible to crowd out 100% of *PetroCoalPrd* in all of Bremen's heavy industries until 2032 due to a positive investment in the H_2 sector's capital stock, the regional effects are fairly negative. The corresponding simulation results (not shown in their entirety here) indicate that industry output in *chemical* (-4.94%), *steel* (-0.81%), and *copper* (-0.25%) will decline, whereas regional GDP (-0.13%) and employment (-0.07%) will remain more or less unchanged. On the basis of these results, it can be fairly assumed that all three industries in Bremen would rather refrain from conducting a total switch in production until the beginning of the 2030s.

Instead, we formulate the following research question: *For which individual switch ratios employed in the different industries does the corresponding change in output become virtually zero?* Hence, we pin down the percentage substitution rates of *PetroCoalPrd* versus H_2 individually for each of the heavy industries, which ensures that no or only a negligible decline in output holds. Via this approach, partial climate-neutral production does not negatively affect economic activity.

The following switch ratios that fulfill this criterion can be identified. The *chemical* industry in

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[6] See the E-Bridge Consulting webpage (accessed on February 25 2024) for more information. Note that the H_2 price is expressed in euro per kilogram (euro/kg). Dividing this number by the upper calorific value of 33.3 and applying the exchange rate gives us the price expressed in USD/kWh.

[7] For their investigation, Doucet *et al.* 2023 also discuss the 'EEX Hydrix' price index (accessed on February 25 2024), for which they consider the 2023 price of 0.239 USD/kWh. This index shows the development of the price that in addition to production costs, includes capital costs, transportation costs, distribution costs, and the profit spread. We do not consider the EEX Hydrix index in our study since, at the time of writing this paper, the (northern) German H_2 core network has not yet been established. With the focus on the switch conducted solely in Bremen (Bremerhaven) without any (extensively possible) shipping of H_2 between regions, we state that it is reasonable to consider the 'Hydex' price index only on the basis of marginal costs excluding margins.

Bremen could lay off 1.5% *PetroCoalPrd* without presumably experiencing any decline in output. Moreover, 15% of fossil fuels can be substituted by H_2 in the *steel* industry. Finally, the highest switch ratio can be considered in the *copper* industry, at 35%. We discuss the industrial and regional effects in Bremen (Bremerhaven) and other regions on the basis of these ratios in the next Section. The interested reader is referred to Appendix A.3 to determine how the production switch is incorporated into EuroTERM via a technology shock.

Transformation of the H_2 Industry

For completeness, we also consider a total, i.e., 100%, crowding out of *PetroCoalPrd* by H_2 in the H_2 sector itself, which can be seen as a required step toward the production of green H_2, i.e., in the absence of fossil energy sources. The latter also includes electricity made out of coal and gas summarized in the commodity *ElecCoalGas*, as well as nuclear power and oil expressed through *ElecOther* in EuroTERM. Both commodities resemble 'gray' types of electricity, as their use causes CO_2 emissions compared with 'green', i.e., emission-free, types.

While electricity production from nuclear power no longer occurs domestically in Germany owing to the 2011 nuclear moratorium (with the last four nuclear power plants going out of commission in 2023), in August 2024, the country imported approximately 8 terawatt hours of electricity from abroad, mainly from its direct neighbor states, France, the Czech Republic, and Poland, which all still rely heavily on nuclear-generated power.[8] In addition, approximately 4.6 terawatt hours of electricity were generated from petroleum products in Germany in 2023.[9] Taking these circumstances into account, together with the fact that we have nonzero entries for *ElecOther* in the base data following Wittwer 2022, we state that for the H_2 industry to come as close as possible to producing green H_2, it should rely heavily on *ElecRenew* and *ElecHydro*. The latter is the last of the 4 electricity-generating industries to be found in our version of EuroTERM and consists of hydropower.

We do not force a switch regarding electricity out of fossil fuel (*ElecCoalGas* and *ElecOther*) and natural sources (*ElecRenew* and *ElecHydro*) to be applied owing to the very high rate of substitution elasticity among these four commodities. Instead, we rely on market adjustments caused by the price mechanism, i.e., changes in the relative prices among commodities, which benefits the less expensive good in terms of higher demand. We consider a uniform initial price level for all types of these nearly perfect substitutable energy products, which implies that the corresponding price gaps are equal to one. After all price adjustments take place, we define and compute the so-called electricity-input ratio (EIR); input is given by the sum of all entries in million US dollars per region and industry regarding the input of electricity generated on the basis of natural sources (i.e., *ElecRenew* and *ElecHydro*) relative to the corresponding sum of all electricity commodities, including those coming from fossil fuel (i.e., *ElecCoalGas*, *ElecOther*, *ElecRenew* and *ElecHydro*). As a result, we are approximating the share of green-type electricity used in the production of H_2, which allows us to discuss how (partially) green H_2 becomes in response to the abovementioned supply shocks.

4.2 Results

The simulation results at the industrial level are presented in Table 2 and are expressed via percentage changes in industry output (x_{IND}) and price (p_{IND}) from the base year 2022 until the final state in 2032. It appears that H_2 output increases massively in those regions that experience high

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[8] See the corresponding webpage of statista.com (accessed on September 15 2024) for more information. Strictly speaking, electricity production from nuclear power is CO_2 emission free. However, we cannot distinguish between the corresponding entries and those related to oil to be found in the database, as both are stored in *ElecOther* by default.

[9] Again, check out statista.com (accessed on September 15 2024).

capital investments, i.e., all except in the four NUTS2 subregions belonging to Lower Saxony for which there are no investments in the H_2 industry. In these regions, H_2 output (like that in the subregions' heavy industries, except for *chemical* in Weser Ems, DE94) increases due to a decrease in the price for intermediate goods used in production caused mainly by the strong increase in the supply for *ElecRenew* according to the last row of Table 2. This finding is not true for the region of Lueneburg (DE93), which faces a strong increase in labor costs, i.e., the real wage (see below), which negatively affects the H_2 industry's cost structure. The changes in both prices for H_2 and *ElecRenew* are negative. These results are consistent with underlying economic theory, according to which an expansion of supply without (or with only partially) changing demand leads to increasing industrial production while decreasing the price of goods.

Table 2. Development of output and prices in selected industries in %.

	DE50		DE60		DE80		DE91		DE92		DE93		DE94		DEF0	
	x_{IND}	p_{IND}	x_{IND}	p_{IND}	x_{IND}	p_{IND}	x_{IND}	p_{IND}	x_{IND}	p_{IND}	x_{IND}	p_{IND}	x_{IND}	p_{IND}	x_{IND}	p_{IND}
Chemical	-0.01	0.00	0.11	-0.01	0.34	-0.05	0.11	-0.02	0.21	-0.03	0.09	-0.02	-0.10	0.01	0.08	-0.02
Steel	-0.01	0.00	0.41	-0.05	0.45	-0.10	0.16	-0.06	0.31	-0.08	0.22	-0.07	0.09	-0.04	0.15	-0.06
Copper	0.01	0.00	0.28	-0.03	0.81	-0.11	0.35	-0.07	0.67	-0.10	0.57	-0.09	0.15	-0.03	0.55	-0.08
H_2	229.31	-42.33	73.95	-26.70	187.30	-38.58	10.43	-11.05	11.07	-11.11	5.94	-11.12	17.13	-12.53	183.14	-40.10
ElecRenew	439.37	-38.95	593.35	-42.85	128.50	-21.47	798.48	-54.87	2912.85	-64.45	550.55	-55.47	35.21	-17.18	130.17	-27.31

Note: The following assignments apply. DE50 = Bremen (Bremerhaven), DE60 = Hamburg, DE80 = Mecklenburg–Western Pomerania, DE91 = Braunschweig, DE92 = Hannover, DE93 = Lueneburg, DE94 = Weser Ems, DEF0 = Schleswig–Holstein, and RoDE = rest of Germany. All entries indicate the deviation of the variable industry output x_{IND} and price p_{IND} relative to the base values given in %.

By targeting the fulfillment of our criterion stated earlier regarding the switch in production toward H_2, Bremen's heavy industries—*chemical*, *steel* and *copper*—show virtually no change in output and prices. Hence, laying off 1.5, 15, and 35% of *PetroCoalPrd* in the above industries, respectively, causes no harm in terms of economic performance but brings Bremen closer to a climate-neutral production scheme. An increase (decrease) in output (prices) is almost entirely observed in all other regions where there is no forced switch in production being applied. In these cases, heavy industries benefit mainly from the sharp decline in the price for *ElecRenew*. The overall development in output and prices across all regions is nevertheless very low; i.e., it amounts significantly to less than a 1% change.

The same can be said of the regional macroeconomic effects, as shown in Table 3. Investment and technology shocks do not cause strong deviations in real GDP, employment, or the real wage. From a macroeconomic perspective, both supply shocks have a barely noticeable impact. First, the increases in capital stock in both the H_2 and *ElecRenew* industries are too low to trigger a significant positive change in income and the number of hours worked. Second, the potential positive transfer effects of a reduction in the H_2 price are small since H_2 is used only in small quantities in a few industries and, therefore, participates only weakly in its price development. Third, regions such as Mecklenburg–Western Pomerania and Schleswig–Holstein, which experience a large amount of investment, attract a considerable number of workers to be employed in fast-growing industries—H_2 and *ElecRenew*, among others—benefiting from low energy costs. This finding is confirmed by looking at the positive changes in both employment and the real wage in both regions. Note, here, that an increase in the capital stock triggers an increase in labor demand according to the underlying Leontief production function. Conversely, higher labor costs impose a burden on labor-intensive industries, such as the *construction* industry, which then produces less output. At the same time, an influx of workers toward Mecklenburg–Western Pomerania and Schleswig–Holstein is mirrored by a lower number of hours worked being available in all of the remaining regions since those workers settle into the two most prosperous regions according to the assumption of labor mobility. Bremen (Bremerhaven) suffers in terms of a decrease in employment, although this number, together with those concerning the development of real GDP and real wage, are very small.

Table 3. Development of selected macroeconomic variables in %.

	DE50	DE60	DE80	DE91	DE92	DE93	DE94	DEF0
Real GDP	0.02	0.17	0.44	-0.02	0.10	0.02	0.00	0.21
Employment	-0.05	-0.03	0.14	-0.01	-0.03	0.00	-0.06	0.05
Real Wage	0.07	0.09	0.26	0.11	0.09	0.12	0.06	0.17

Note: see Table 2.

Finally, we are left with the question of whether the H_2 produced until 2032 turns out to be CO_2 emission free and green. While *PetroCoalPrd* is crowded out completely by H_2 in the H_2 industry itself, the use of *ElecCoalGas* and *ElecOther* declines considerably in response to supply shocks because of the underlying price mechanism that results in a decrease in the relative prices for *ElecRenew* and *ElecHydro* versus those for *ElecCoalGas* and *ElecOther*. Table 4 shows the corresponding EIRs given in % for all regions under consideration of the individual regional price gaps, which are uniformly close to one. We find that in Bremen (Bremerhaven), 74.10% of all electricity used in the production of H_2 stems from green energy sources. We obtain a similar value of 77.43% for the region of Braunschweig (DE91). Hence, the H_2 produced in these regions does not become entirely green until the end of the observation period. The criterion for green H_2 is rather fulfilled in the regions of Mecklenburg–Western Pomerania (DE80; with an EIR of 98.16%), Lueneburg (DE93; 94.21%), Weser Ems (DE94; 96.63%) and Schleswig–Holstein (DEF0; 96.73%).

Table 4. EIR values in % in all northern German regions.

	DE50	DE60	DE80	DE91	DE92	DE93	DE94	DEF0
EIR	74.10	16.41	98.16	77.43	12.25	94.21	96.63	96.73

Note: see Table 2.

All the abovementioned regions therefore meet the requirements stated in the newly introduced article 22a of Directive (EU) 2023/2413 (EU-Parliament and -Council 2023), whereby at least 42% of the H_2 used in industries located in EU member states should be based on renewable energy sources by 2030. This proportion is to be further increased to 60% by 2035. By inspecting Table 4, it seems that this requirement is already met until 2032 for the vast majority of regions on the basis of our simulation. Exceptions are the regions of Hamburg (DE60) and Hannover (DE92), for which we find EIRs of 16.41% and 12.25%, respectively. Our observations imply that in both major cities, electricity based on fossil fuels is still used heavily when producing H_2. Hence, it seems that in Hamburg and Hannover, the amount of electricity that stems from natural sources (i.e., *ElecRenew* and *ElecHydro*) is not high enough to prevent the production of gray H_2. This finding is in line with the existing low investment numbers shown in Table 1, such as, for example, 81.70 million US dollars in Hamburg.

5 Discussion

The simulation results suggest that the transition to H_2 energy in Bremen is economically promising and a key step toward a zero-carbon industry, aligning with previous research on the potential of H_2 to replace traditional fuels without disrupting industrial output or pricing. However, the availability of renewable electricity is a prerequisite, as current electricity prices are too high to facilitate this transition. Nevertheless, the simulation indicates that declining H_2 prices could lead to economic viability, particularly benefiting regions with high capital investments, such as Mecklenburg–Western Pomerania and Schleswig–Holstein.

The H_2 transition offers a viable pathway for decarbonizing Bremen's industries with minimal economic disruption. However, regional disparities call for targeted policies to encourage green H_2 adoption and meet the EU's future climate targets across northern Germany. Industries must also increase energy efficiency, intensify recycling efforts, and shift to low-carbon production methods to meet the EU's emission reduction goals. H_2 has emerged as the most promising clean energy source in the 21st century because of its diverse origins, high calorific value, and efficient thermal conductivity (Liua *et al.* 2021) and is distinguished by its high combustion heat and pollution-free production process (Wang *et al.* 2021). Unlike electricity, H_2 serves as a fuel that can be transported over long distances via established methods such as sea transport and pipelines, making it a potential game changer for the *steel* industry (Liua *et al.* 2021).

Importantly, it is overly simplistic to assume that H_2-based steelmaking will automatically be the preferred choice for all sites. In particular, the *iron* and *steel* industries are often slow to adapt to large-scale transitions (Karakaya, Nuur, and Assbring 2018). Strategies employed by individual companies, along with effective management or a well-developed regional infrastructure, can significantly influence the success of H_2 adoption within the steel market (Schneider 2022, Toktarova *et al.* 2022). However, this does not mean that the transformation will be successful; the German and European steel markets have experienced recurring crises in their development. In fact, the *steel* industry has been in a state of perpetual crisis since 1975, which can be attributed to, among other factors, a significant functional disturbance within the market. The market structure is characterized by interventionist tendencies, a lack of responsiveness, and market indivisibilities. In contrast, market dysfunctions have been mitigated in line with EU treaties and EU single-market development (Blanckenburg and Kubani 2007). However, there is still a tendency for a market gap between the supply and demand of steel products (due to existing overcapacity) and market uncertainties to emerge (Voegele *et al.* 2020).

The substantial capital investments in H_2 infrastructure and industrial transformation are facing further uncertainty because of Germany's comparatively high energy costs in the global market. The country is currently also on the brink of a technical recession, which could further dampen demand in the steel market. These economic challenges may hinder Germany's ability to compete internationally, as steel production might become less economically viable domestically, and demand for steel products could decline. This market impact is recognized by politicians. Germany is the largest steel producer in Europe, particularly in terms of crude and primary steel production. Although the *chemical* industry demands significant amounts of H_2, the German government's H_2 strategy focuses primarily on transforming the *steel* industry to reduce CO_2 emissions (Otto *et al.* 2017; Voegele *et al.* 2020), thereby advancing toward the goal of climate neutrality by 2045 (Bolz, Thiele, and Wendler 2024). This strategy is supported by the European Commission, which considers H_2 a key pillar of the planned 'European Green Deal' (European Commission 2020). However, several steel companies in Europe have begun exploring H_2-based steel production methods (Öhman, Karakaya, and Urban 2022).

6 Conclusion

Our simulation results, which are based on a large-scale theoretical macroeconomic model, provide benchmark values for discussing the transition to a H_2 economy in northern Germany. These results are in line with those discussed in Sacht 2024, which focuses solely on the development of output and prices related to the H_2 sector in all regions of northern Germany until 2030, without any switch in production toward H_2 being considered. Our simulation results indicate that Bremen's *chemical*, *steel* and *copper* industries could lay off 1.5, 15 and 35% of the amount of fossil fuel in production, respectively, and substitute it with H_2, without any negative effects on their industries' production and prices. The corresponding amount of H_2 represents approximately 74% of renewable energy in production, without any petroleum, coal, or natural gas used as input factors.

Our study also reveals regional disparities in the impact of the H_2 transition. Most regions experience positive economic effects; e.g., Lueneburg (DE93) faces rising labor costs, which limit its industrial growth. Additionally, although regions such as Bremen and Braunschweig are on track to meet the EU's 2030 renewable energy targets for H_2 production, Hamburg and Hannover still rely heavily on fossil-fuel-based electricity, which underlines the need for further investments in renewable energy infrastructure in these regions. At the macroeconomic level, the H_2 transition has only a minor impact on real GDP and employment because of the relatively small role that H_2 currently plays in the energy mix. However, regions with greater investments in H_2 and renewable energy, such as Schleswig–Holstein and Mecklenburg–Western Pomerania, experience positive effects on employment and wages.

A follow-up analysis around 2030 would be valuable to assess if the model results remain relevant and accurately reflect the evolving conditions, ensuring that the findings align with the real-world progression of H_2 integration in the region. Significant uncertainty lies in whether the steel market will successfully transition toward green H_2. The current market situation, characterized by business cycles and substantial investments in capital stock combined with global steel demand, may also result in the relocation of steel production to other parts of the world, such as India. This potential shift underscores the importance of monitoring global dynamics and local investment conditions in the *steel* industry as part of future research.

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Appendix

A Important Key Equations

In the following, we show how the values of shock variables $a^{FIN}_{j,REG}$, $a^{INT}_{H2,IND,REG}$ and x^{CAP}_{j} for $j \in \{H2, ER\}$ are numerically computed via key equations based on EuroTERM. Small (capital) letters indicate, in general, percentage changes (levels) in the model variables. The following abbreviations apply. FIN and INT are linked to a specific technology shock, a, and denote the final industry output and intermediate good, respectively. CAP and x stand for the value of capital rentals and the percentage change in quantity, respectively. The H_2 (*ElecRenew*) industry IND has the abbreviation $H2$ (ER). Note that $REG \in$ {DE50, DE60, DE80, DE91, DE92, DE93, DE94, DEF0} applies.

A.1 Technology Shock

$a^{FIN}_{j,REG}$ denotes an all-input-augmenting technical change measuring the level of corresponding productivity affecting energy production in industry j and region REG. Moreover, $a^{FIN}_{j,REG}$ represents the change in the amount of all inputs needed to produce one unit of final industry output. According to this representation, the shock is Hicks neutral; i.e., it affects all inputs equally. $a^{FIN}_{j,REG}$ is part of the demand schedule for primary factor composites (labor, capital, and land) as a result of minimizing the industry's cost function comprising expenditures on intermediate goods, primary factor composites and 'other costs' subjected to the Leontief production function, with the latter assuming that the components of production will be used in fixed (technologically preset) proportions since the factor substitutability value is zero. The composition of demand for primary factors is proportional to the final industry output $x^{FIN}_{j,REG}$. Considering the corresponding price change in primary factor composites, the final output changes in response to quantity adjustments in labor $x^{LAB}_{j,REG}$, capital $x^{CAP}_{j,REG}$ and technology $a^{FIN}_{j,REG}$; i.e.,

$$x^{FIN}_{j,REG} = \psi_{LAB} \cdot x^{LAB}_{j,REG} + \psi_{CAP} \cdot x^{CAP}_{j,REG} - a^{FIN}_{j,REG} \tag{A1}$$

applies, where $\psi_{LAB} > 0$ ($\psi_{CAP} > 0$) denotes the value share of labor (capital) in primary factor costs. Note that a negative value for $a^{FIN}_{j,REG}$ implies a positive percentage change in productivity. According to equation (A1) above, this leads, ceteris paribus, to a positive stimulus on final industry output $x^{FIN}_{j,REG}$. This kind of productivity gain indicates an improvement in the degree of efficiency of electrolysis as well as the electricity-generating process, as discussed in the main text. In particular, we consider

$$a^{FIN}_{H2,REG} = -11 \quad \text{and} \quad a^{FIN}_{ER,REG} = -10$$

until 2032 for all regions of northern Germany belonging to the set REG.

A.2 Investment Shock

Equation (A1) implies that percentage changes in capital stock $x^{CAP}_{j,REG}$ have a direct effect on the change in final industry output $x^{FIN}_{j,REG}$. In addition to changes in technology via $a^{FIN}_{j,REG}$, we consider this type of supply shock explicitly. Note that according to the underlying base data, capital rentals $CAP_{j,REG}$ rather than stocks are statistically reported. In this paper, we synonymously employ both expressions: as industries rent capital for use in production, we must consider the corresponding rental rate (price) of capital. That is, if capital had been rented out somewhere else instead of being utilized for production, then the rental rate of capital would have been the opportunity cost of the missed income. It follows that we denote r_j as the rental rate, which also stands for the return on equity on the basis of the industry's evaluation of its own capital stock.

The value of capital rentals reported in the base data is denoted by $CAP_{j,REG}$. Let $INV_{j,REG}$ be investment evaluated at purchaser prices on the basis of the 'Hydex' price index in each singular region per industry; under consideration of the return of equity r_j, we arrive at

$$x^{CAP}_{j,REG} = \frac{INV_{j,REG} \cdot r_j}{CAP_{j,REG}}, \tag{A2}$$

where the product of the newly installed capital stock $INV_{j,REG}$ (in million USD) and the rental rate r_j allows for the evaluation of additional capital that can potentially be rented out. Considering this in relation to the existing capital stock $CAP_{j,REG}$ (in million USD) prior to the shock gives us the percentage change in capital rentals from one steady state to the next. We assume that there is no capital depreciation for simplicity since we apply a comparative statics analysis.

We consider the following rental rates:[10]

$$r_{H2} = 0.069 \ \text{ and } \ r_{ER} = 0.035.$$

With respect to investments in capital stock until 2032, $INV_{H2,REG}$ and $INV_{ER,REG}$ can be obtained from Table 1 in Section 4.1. Note that investments in *ElecRenew* also include numbers for the RoDE region in addition to those stored in the set REG, as stated above.

Moreover, there exists a negative relationship between the change in capital rentals $x^{CAP}_{j,REG}$ and the associated price level denoted by $p^{CAP}_{j,REG}$ as follows:

$$p^{CAP}_{j,REG} = -1/\sigma \cdot x^{CAP}_{j,REG}, \tag{A3}$$

where $\sigma > 0$ is the parameter measuring the substitution elasticity between primary factors, i.e., the proportional change in input ratios per change in relative input prices. A positive investment shock leads to the price for capital declining and, hence, relaxes the cost structure of the industry, which, in turn, leads to higher industry output.

A.3 Production Switch

$a^{INT}_{H2,IND,REG}$ denotes the intermediate technology change regarding H_2 used in industry IND and region REG. Its counterpart is given by $a^{INT}_{PET,IND,REG}$, where PET denotes the commodity *PetroCoalPrd*. Equivalent to the technology shock that affects the final stage of production, here, the intermediate demand for this specific input good, i.e., either *H₂* or *PetroCoalPrd*, changes. Hence, a productivity gain expressed through a negative value for the exogenous shock variable leads to less of the particular intermediate good needed for production, and vice versa.

We set

$$a^{INT}_{PET,IND,DE50} = -\beta_{IND} \tag{A4}$$

across the heavy industries—*chemical*, *steel* and *copper* —in the region of Bremen (Bremerhaven), that is, $DE50$, which indicates that the demand for *PetroCoalPrd* is reduced by β_{IND}%, as the selected industries seek to lay off fossil energy sources used in production. In the main body of the text, we show that for

$$\beta_{Chemical} = 1.5, \ \beta_{Steel} = 15, \ \text{and } \beta_{Copper} = 35,$$

heavy industries exhibit virtually no change in industry output due to a costly switch to H_2. The

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[10] Information on the return of equity is taken from energie-und-management.de and ebnerstolz.de (both accessed on July 21 2024).

corresponding increase in demand for H_2 is computed via

$$a^{INT}_{H2,IND,DE50} = \frac{P_{H2,DE50}}{P_{PET,DE50}} \cdot \beta_{IND} \cdot \frac{USE^{INT}_{PET,IND,DE50}}{USE^{INT}_{H2,IND,DE50}}, \tag{A5}$$

where $P_{z,DE50}$ for $z \in \{H2, PET\}$ denotes the price level of the regional composite that holds prior to simulation. Hence, the first term in equation (A5) denotes the price gap ratio based on the price level for H_2 versus that for *PetroCoalPrd* and is given by the factor 2.33, as stated in the main body of the text.

$USE^{INT}_{z,IND,DE50}$ denotes the corresponding delivered value of demand. The latter part of this term states how much of the particular intermediate good is used in the production process per IND for $DE50$ expressed in million US dollars and is taken directly from the initial database. According to equation (A5), the change in the demand for H_2 needed to crowd out *PetroCoalPrd* depends on the initial price gap ratio and how much *PetroCoalPrd* is used relative to H_2 before the switch displayed by the second term.

As mentioned in the main body of the text, for completeness, we also consider a switch of 100% being conducted in the H_2 industry across all regions; i.e.,

$$a^{INT}_{H2,H2,DE50} = \frac{P_{H2,REG}}{P_{PET,REG}} \cdot \beta_{H2} \cdot \frac{USE^{INT}_{PET,H2,REG}}{USE^{INT}_{H2,H2,REG}} \tag{A6}$$

with $\beta_{H2} = 100$.