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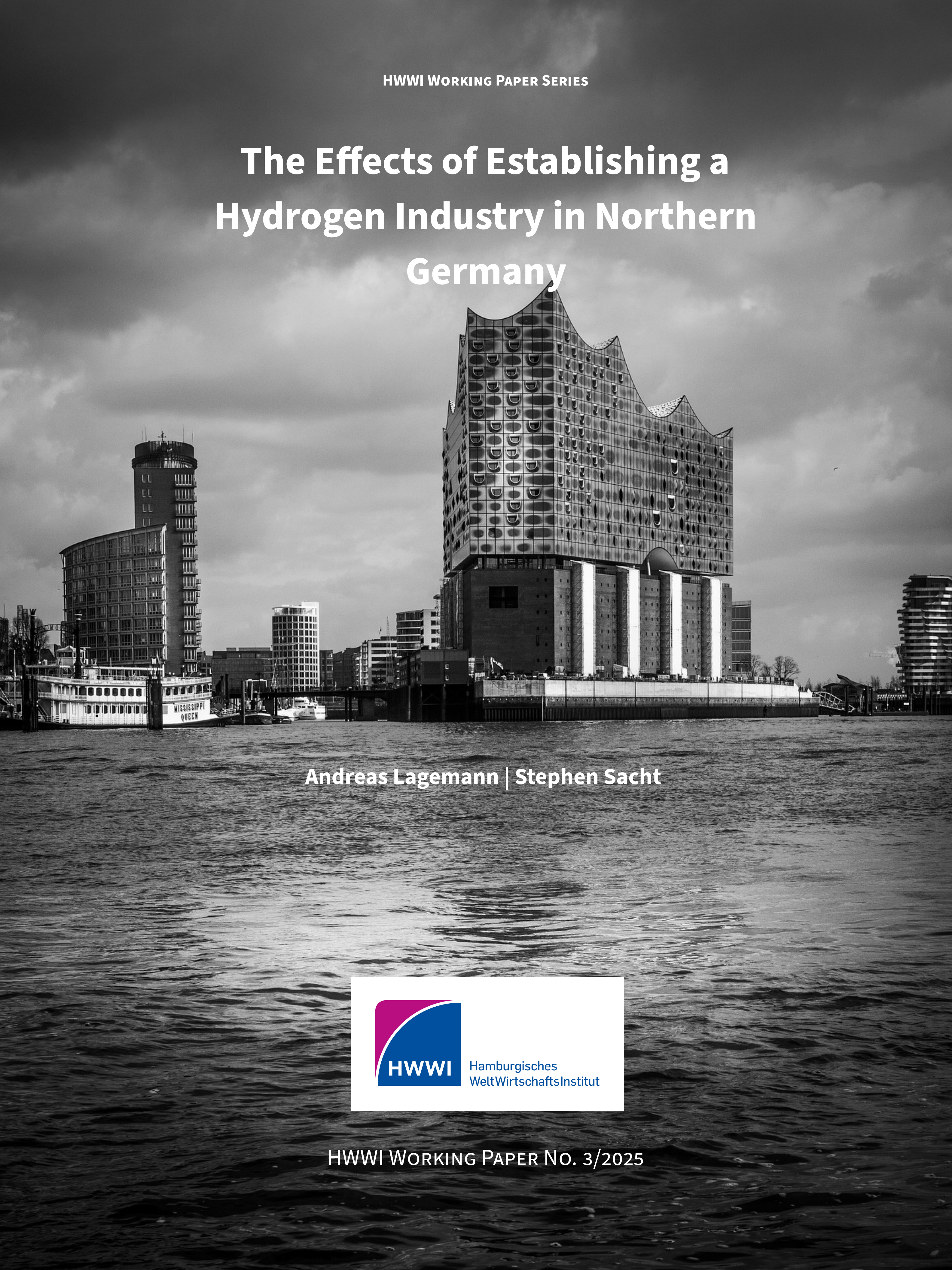

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The Effects of Establishing a Hydrogen Industry in Northern Germany

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Abstract

Currently, achieving sustainable transformation toward a carbon-dioxide-free industrial production process is one of the greatest challenges. The chemical element hydrogen used as an energy source and a basic feedstock can play an important role in reaching this goal. Our analysis is based on the CGE framework and focuses on a total switch toward hydrogen used in production in northern Germany until 2045. The simulation results indicate that such a cost-intensive procedure can lead not only to a negative development in regional GDP and employment but also to a decline in the output of heavy industries such as chemical, steel, and copper. Reverse effects are obtained in the case of further deregulation, which has the potential to increase the efficiency of an established hydrogen core network. This observation emphasizes the need to accompany the transformation process by maintaining low-level regulation.

Keywords: Computable General Equilibrium Model Analysis, Hydrogen Economy, Regional and Industrial Development, Northern Germany, Regulations.

JEL classification: C68, O13, Q21, R13

1 Introduction

Hydrogen is a key enabler of the energy transition, offering a clean, flexible, and scalable alternative to fossil fuels, especially in industry, heating, and mobility. Hydrogen plays a crucial role in decarbonizing high-emission sectors such as steel and chemical sectors, where fossil fuels are used traditionally for high-temperature processes and as raw materials. In the steel industry, hydrogen can replace coal in direct reduction processes, significantly reducing CO_2 emissions, whereas in the chemical industry, it serves as a feedstock for ammonia, methanol, and synthetic fuels. Hydrogen also supports renewable energy integration by storing excess wind and solar power through electrolysis, thus ensuring a stable and reliable energy supply. In transport, fuel cell vehicles offer long ranges and fast refueling, making them ideal for heavy-duty applications, whereas hydrogen production generates waste heat, which can be repurposed for district heating, thus improving overall energy efficiency. By fostering sector coupling, hydrogen connects power, heat, industry, and transport, creating a more integrated and sustainable energy system while reducing CO_2 emissions (Willich 2024).

The joint project Norddeutsches Reallabor (NRL), funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK), with additional support from the Federal Ministry of Digital and Transport (BMDV), began in 2021 to promote the production and usage of hydrogen in different applications in northern Germany. The project aims to install seven electrolyzers with a total capacity of 40 MW to produce green hydrogen to replace fossil fuels in industrial processes. In the mobility sector, hydrogen refueling stations and fuel cell vehicles are being tested under real-world conditions. With over 50 business, science, and political partners, the project fosters sustainable innovation, economic growth, and energy independence. Covering Hamburg, Schleswig-Holstein, Mecklenburg-Western Pomerania, and Bremerhaven, the NRL structures sector integration into

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geographic hubs that align with the power and gas grid infrastructure. At strategic locations, hydrogen production clusters are established to decarbonize local consumption centers, serving as a model for large-scale hydrogen-based sustainability in Germany and Europe.[1]

As contributors to the NRL project, in this study, we consider a microfunded macroeconomic model that depicts the regional and industrial effects of various disturbances in line with the overarching story of establishing a hydrogen economy in northern Germany. With a primary focus on developments in the federal states of Schleswig-Holstein, Hamburg, Bremen, Mecklenburg-Western Pomerania, and Lower Saxony, we elucidate the impact of supply and demand shocks on the selected industries. By distinguishing between an investment phase and an operational phase, we run simulations to pin down the adjustments in key economic variables. Therefore, in this study, we allow for i) the build-up of a (green) hydrogen industry via investment and technology shocks, ii) a switch away from fossil-based energy toward hydrogen exclusively used in production, and iii) an analysis of the role of (de)regulatory measures regarding the distribution of hydrogen via a core network.

The remainder of this paper is structured as follows. In the next section, we describe the computable general equilibrium (CGE) methodology and highlight the main features of our analysis. In Section 3, we provide a review of the literature linked to our study. In Section 4, we specify the shock scenario and present the main results—at the industry and regional levels—obtained via simulations for the investment phase. This section is followed by Section 5, which addresses the setup and findings for the operational phase. In Section 6 we discuss the effects of (de)regulations. Section 7 concludes the paper. The computational steps and additional material are relegated to the Appendix.

2 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 macroeconomics, 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. Those observables are expressed as the product of quantity multiplied by the price of 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, this 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, that is, 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 the total differential approach.[2] Despite the existing approximation error relative to a nonlinear representation, a linearized model exhibits a closed-form reduced solution and hence becomes much more manageable mathematically than does a nonlinearized model.

The microfoundation implies that agents' decision-making process stems from determining the optimal outcome of their objective function conditional on available resources. For example, each

1. For more information, the interested reader may visit norddeutsches-reallabor.de.
2. 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) values of the variables X and Y 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 with 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 changes 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.

industry in the economy minimizes the costs of producing its output by selecting sufficient number of inputs, that is, labor, capital, and intermediate products. The industry's investment schedule depends on the movement in the 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. This situation implies that in the case of a decrease in input costs (e.g., a drop in real wages), industries demand more of the specific input (in this case, labor) for use in the production process until all costs at the margin are covered entirely by the market price for industry 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).[3]

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. TERM represents a large-scale system of equations and 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 (NUTS) level, which we refer to as NUTS2. 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), with the latter collecting and providing 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 the TERM in general is provided by Horridge 2011 and, more specifically, for the EuroTERM is provided by Wittwer 2022.[4]

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 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, thus creating 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 the 8 subregions that form northern Germany. These regions (with NUTS2 codes in parentheses) are Schleswig-Holstein (DEF0), Bremen and Bremerhaven (DE50), Hamburg (DE60), Mecklenburg-Western Pomerania (DE80) and Lower Saxony (comprising DE91 to DE94). In addition, we obtain data for the rest of Germany (RoDE), the rest of Europe (RoE), the US and China. However, we refrain from reporting results for all

3. It becomes obvious that feedback effects can occur as prices adjust in response to disturbances that hit 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 or demand of labor), this situation causes a change in the real wage to restore the final equilibrium. As a result, real wage adjustments affect industries' cost structure as the price for the input labor changes. The effect is more pronounced when more labor is intensively used in the production process across industries and so on.

4. To run simulations, the user is required to make changes to the core structure of the model and specify the magnitude of shocks. In addition, the automatic 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. 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) and data obtained from the GTAP data base, version 11 (Aguiar *et al.* 2022).

regions other than northern German regions since the impact of shocks on the large RoDE, RoE, USA, and China economies, together with the occurrence of potential feedback effects, turns out to be negligible.

For a clear arrangement and better manageability, we consider only 33 out of 74 industries in our simulations. The focus is on so-called heavy industries such as *chemical*, *steel* and *copper*, as well as *renewable electricity* and *hydrogen*. *Hydrogen* is considered an embryo, i.e., a tiny industry with a low level of endowments regarding intermediate goods, primary factors, overall output, and so on. This assumption holds since the *hydrogen* industry is close to nonexistent at the beginning of our simulations, with the (first) base year, 2023, as a starting point. 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 *hydrogen* in the 2017 database are set. This practice of parameterizing newly established industries is common in CGE modeling.

We conduct a comparative-static analysis, i.e., a comparison of the results obtained for the initial and final equilibrium states. In EuroTERM, these results are expressed via changes in the model variables in percentage terms relative to the base from one state to the other. We follow a long-term closure, as we address periods from 2023 until 2030 and until 2045. This type of closure reflects the assumption that capital is endogenously determined, while employment is held fixed. The latter applies, however, only to the national aggregate of employment. Hence, for Germany as a whole, we observe changes only in the real wage. In contrast, across the different German subregions (including the RoDE), employment alongside the real wage is endogenous with a low degree of labor mobility, which 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 base and updated matrices are balanced, i.e., that there are no significant numerical deviations in the supply from the demand schedules (or vice versa) to be observed such that the general equilibrium paradigm is appropriate.

3 Literature Review

From a broader economic and technological perspective, green hydrogen is increasingly viewed as a promising tool in Germany's transition to a low-carbon economy, particularly for decarbonizing hard-to-abate sectors. Although its use in heating is less efficient than is that of alternatives such as heat pumps and while direct electrification remains the preferred option for most road transport, hydrogen finds its niche in sectors such as shipping and aviation—areas where electrification is not yet a viable alternative. Overall, the literature consistently identifies the most promising applications of green hydrogen in industries that are difficult to decarbonize, including steel, copper, and chemical production (Doucet *et al.* 2024).

Research by Doucet, Jürgens, *et al.* (2023) indicates that green hydrogen works effectively as a reducing agent in several industrial processes, although it is not applicable for every sector; for instance, green hydrogen falls short in aluminum and cement production. The above analysis underscores that the economic feasibility of green hydrogen is closely tied to the prices of natural gas and hydrogen itself. In the context of the metal industry, studies focusing on Hamburg (Schütte *et al.* 2022) suggest that onsite hydrogen production for iron and copper manufacturing could become economically attractive over the next decade. This positive outlook depends on continued declines in renewable energy costs and increases in carbon pricing, factors that would shift the cost balance in favor of hydrogen-based processes. Moreover, in the chemical industry, Jürgens and Schäfers (2024) highlight that closing the cost gap between green and conventional hydrogen hinges largely on reducing electricity prices and managing high capital expenditures associated with advanced electrolysis technologies. The above authors note that fluctuations in natural gas prices can also temporarily narrow this gap, further emphasizing the importance of market conditions in determining the economic viability of green hydrogen.

However, the development of green hydrogen in Germany is challenged not only by technological and economic factors but also by an unclear legal framework and evolving sustainable finance requirements. The existing legal regulations for renewable hydrogen are fragmented and inconsistent (Hoffmann, Kamm, and Pause 2023), creating uncertainty for both producers and end users and complicating long-term investment planning. This legal ambiguity, coupled with sustainable finance rules that impose extensive reporting and compliance obligations (Düsterlho and Mohr 2023), adds to the financial and administrative burden placed on companies. Consequently, these regulatory challenges can deter investments in green hydrogen infrastructure, making it imperative for policymakers to establish a more coherent and supportive legal environment that aligns with sustainable finance principles to ensure stability and foster industry growth.

Owing to the nature of the subject matter at hand, macroeconomic studies incorporating hydrogen as input in production are rather scarce. To our knowledge, we are among the first to investigate the effects of establishing a hydrogen industry at the regional level for the entirety of northern Germany via CGE model analysis. Mueller and Gronau 2023 note that there are no explicit hydrogen-related CGE studies at the country level for Germany prior to 2024. The interested reader is referred to their survey article, where the above authors provide a detailed overview of the recent CGE literature related to hydrogen. For a more general review on 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 hydrogen sector in northern Germany. Using EuroTERM, his simulation results indicate a drop in the industry price for hydrogen across all northern states and, hence, a potential narrowing of the price gap between hydrogen and fossil fuel after 2030.

A small selection of papers (involving CGE models) addresses the development of energy prices, regulatory measures, and changes in production technology related to hydrogen. Maestre, Ortiz, and Ortiz 2021 discuss the cost-competitiveness of hydrogen as an energy source over fossil fuel and highlight existing regulations and barriers in terms of legal framework, environmental impact, infrastructure, safety, and social factors that may have a negative impact on establishing a hydrogen infrastructure. With a focus on chemical manufacturing in 6 Asian regions, Lee 2020 investigates different types of improvements in technology related to biohydrogen production, i.e., hydrogen generated from biomass. In an earlier work, Silva, Ferreira, and Bento 2014 study the economic effects of hydrogen used in the Portuguese road transport sector and show that advances in hydrogen-powered vehicle transportation technologies may have a positive effect on macroeconomic variables such as household consumption (+2.4 to +2.9% change) and GDP (+2 to +2.4% change) until 2050. Finally, 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 of achieving carbon neutrality by 2060. The above authors claim that a hydrogen-based switch of 23 to 25% in the production process should be implemented by 2050 to meet the carbon oxide mitigation target.

4 Investment Phase

By choosing suitable model parameter values, specific conditions can be considered in different markets. This type of parameterization is carried out transparently for the respective application, considering the regional economic structures (expressed through input–output relationships).

Following the notation applied in EuroTERM, we refer to electricity generated from wind and solar (photovoltaic) energy simply as *elecrenew*, while we speak of *hydrogen* and H_2 synonymously. Fossil fuel, as an input factor in production, consists of petroleum, coal, and natural gas. We summarize these types of energy sources as the commodity *petrocoalprd*. Throughout our analysis, we consider the US dollar (USD) to Euro spot exchange rate (DEXUSEU) given by 1.1 as of June 1st, 2024, to convert expressions given in million Euro into the foreign currency of choice. All these assumptions and definitions apply to both the investment and operational phases, respectively.

4.1 Shock Scenario

Technology Improvement

We assume that the inputs utilized to produce *elecrenew* are 10% more efficient than are those utilized to produce *hydrogen*, which is consistent with the situation in all northern German regions. Hicks neutrality suggests that this type of technology shock is similar to an increase in productivity across all inputs, which results in a reduction in the number of intermediate goods and primary factors (i.e., labor and capital) needed to create a given unit of output. What follows is a loosening of the industry's cost structure, which raises output levels ceteris paribus, i.e., for the price level remaining unchanged.

Because we now observe degrees of efficiency of 45-50% for wind and 14-20% for solar, we take some liberties regarding the assumption for the corresponding change in *elecrenew* production. Concerning the electrolysis process, however, we assume a shift in the degree of input efficiency of 11% in the creation of hydrogen. The latter resembles an improvement based on the power-to-gas approach to hydrogen from 59–70% until 2030 according to Maier 2018. 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

Capital stock will presumably grow in the *elecrenew* and *hydrogen* industries until 2030. Data on planned investment in electricity from renewable energy sources are provided in the Federation-Länder Cooperation Committee's 2022 and 2023 reports, which offer information on an annual basis about the state of expansion of renewables in Germany (Bund-Länder-Kooperationsausschuss 2022, 2023). By focusing on off- and onshore windmills plus solar panels, we consider numbers for newly installed net capacities in each region of northern Germany as well as the remaining country in 2021 and 2022. Owing to data availability, we extrapolate these investment numbers eight years into the future until 2030; i.e., we pretend that every two years, the same amount of new capacity given in megawatts is built for simplicity. All the entries are expressed in megawatts per hour (mWh) under consideration of 2216 full load hours per year (Schlesinger *et al.* 2014). By multiplying these numbers by the 2021 price for electricity of 346.17 USD/mWh (taken from https://strom-report.com/), the amount of investment evaluated at purchaser prices expressed in million USD is computed, which is required for our simulations via EuroTERM. See Table 1 for more details.[5]

Information on planned investment in electrolysis capacity given in megawatts by a plethora of firms in northern German regions has been obtained by researching publicly available data online but only for Bremen (Bremerhaven), Hamburg, Mecklenburg-Western Pomerania, and Schleswig-

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. We take some liberty here and distribute the total amount of the state's investment given in 5,620.16 million USD equally across all subregions.

Table 1. Investment in the *hydrogen* and *elecrenew* industries until 2030 (in million USD).

	DE50	DE60	DE80	DE91	DE92	DE93	DE94	DEF0	RoDE	Total
elecrenew	45.41	65.35	3,024.57	1,405.04	1,405.04	1,405.04	1,405.04	3,393.09	40,283.23	52,431.81
hydrogen	739.01	169.44	1,388.29	–	–	–	–	1,490.91	–	3,787.65

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 newly installed capacities in gigawatts can be obtained from Table A.1 in the Appendix.

Holstein. All the numbers are converted to mWh via 4000 full load hours per year according to Doucet, Düsterlho, *et al.* 2023, who argue that the 2023 price for (green) hydrogen amounts to 0.24 USD per kilowatt hour (USD/kWh). This value is based on the price index "EEX Hydrix" published by EEX AG, which resembles the marginal costs for producing hydrogen, including margin costs, i.e., expenses related to transport and shipping.[6] In particular, this value shows the development of the price that in addition to production costs, includes capital costs, transportation costs, distribution costs, and the profit spread.[7] We are left with the entries in the third row of Table 1 by multiplying the investment numbers by the number of full load hours and the price given in USD/mWh. We use these entries to compute the percentage change in the capital stock in all regions until 2030. Detailed technical information is provided in Appendix A.2.

4.2 Discussion of Results

Effects at the Industry Level

The percentage changes in industry output (x_{IND}) and price (p_{IND}) from the base year, 2022, until the final state in 2030 are presented in Table 2. Not surprisingly, the magnitude of the change in the *hydrogen* industry is positively related to the number of capital investments in the regions of Bremen (Bremerhaven, DE50), Hamburg (DE60), Mecklenburg-Western Pomerania (DE80), and Schleswig-Holstein (DEF0). In contrast, the four NUTS2 subregions DE91-94 belonging to Lower Saxony experience a weak increase in hydrogen production, although there are no investments in this industry at all. This situation can be explained by a decrease in the price for intermediate goods used for producing H_2 caused mainly by the strong decline in the price for *elecrenew* according to the last row of Table 2. The effect on intermediate goods prices is dampened by an increase in labor costs, i.e., the regional average real wage (see Table 3 below), with decisive effects on the change in output despite high investment figures, e.g., in Mecklenburg-Western Pomerania (DE80). In general, positive changes in output are accompanied by negative development in prices. This finding is consistent with the underlying economic theory, according to which an expansion of supply without (or only partially) changing demand leads to an increasing level of industrial production while decreasing the price of goods.

Overall, the development in the output of heavy industries is positive but significantly less than unity. Going forward, we interpret percentage changes smaller than 0.10 in modulus as a state of stagnation. This situation applies to the region of Weser Ems (DE94), for which we find a decline in

6. See https://www.eex-transparency.com/hydrogen/germany 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, Düsterlho, *et al.* 2023 also discuss the price index "Hydex", for which they consider the 2023 price of 0.18 USD/kWh (taken from https://e-bridge.com/competencies/energy-markets/hydex/). We do not consider "Hydex" in our study since it is based on marginal costs *excluding* margins. In our case, this consideration would imply that the shipping process of hydrogen between regions via the newly established (northern) German hydrogen core network—especially during the operational phase after 2030—is not priced accordingly. Therefore, we consider the "EEX Hydrix" instead.

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	0.10	-0.01	0.11	-0.01	0.26	-0.04	0.11	-0.02	0.19	-0.03	0.09	-0.02	-0.05	0.01	0.09	-0.02
Steel	0.15	-0.02	0.34	-0.04	0.34	-0.08	0.15	-0.06	0.29	-0.07	0.22	-0.06	0.11	-0.04	0.17	-0.06
Copper	0.15	-0.02	0.24	-0.03	0.64	-0.09	0.30	-0.06	0.58	-0.09	0.50	-0.08	0.16	-0.03	0.47	-0.08
hydrogen	192.12	-39.06	53.31	-22.05	172.76	-36.57	13.10	-10.93	13.35	-10.98	9.12	-10.99	17.37	-12.03	142.12	-34.77
elecrenew	324.97	-33.49	444.40	-37.45	92.83	-17.64	786.86	-52.95	2,865.88	-62.72	554.40	-53.75	27.94	-14.10	94.43	-22.24

Note: See Table 1. All entries indicate the deviation of the variable industry output x_{IND} and price p_{IND} relative to the base values given in %.

chemical output of only 0.05%. In the majority of cases, heavy industries benefit mainly from the sharp decline in the price of *elecrenew*. The effect is relatively more pronounced going from the *chemical* industry to the *steel* and *copper* industries. The exceptions are Bremen (Bremerhaven, DE50) and Hamburg (DE60), where in the latter, the level of *steel* production increases more than does that of *copper*. However, the overall development in output and prices across all regions is nevertheless at a very low level.

Effects at the Regional Level

Table 3 implies that regional macroeconomic effects are also rather negligible, i.e., that real GDP, employment, and the average real wage remain virtually unaffected by investment and technology shocks. Hence, from a macroeconomic perspective, both supply shocks have a barely noticeable impact. Significant relatively high positive changes in income and hours worked are rare except, perhaps, for the region of Mecklenburg-Western Pomerania (DE80). Potential positive transfer effects stem mainly from reductions in the regional *elecrenew* prices and not so much from that in the price of H_2 since the latter is used only in small quantities in a few industries and, therefore, participates only weakly in the overall development of energy prices. The development of the average real wage indicates that there is an influx of employees into regions such as Mecklenburg-Western Pomerania (DE80) and Schleswig-Holstein (DEF0) due to existing labor mobility. In general, regions that experience a high amount of investment attract a considerable number of workers to be employed in the fast-growing *hydrogen* and *elecrenew* industries, among others, benefiting from low energy costs. Note that the increase in the capital stock goes hand in hand with an increase in labor demand according to the underlying Leontief production function. High labor costs, however, negatively affect labor-intensive industries such as the *construction* industry as their cost structure tightens. The absorption of workers in specific regions with higher real wages also leads to a decline in the other regions' work force since those workers settle into the two most prosperous regions according to the assumption of labor mobility.

Table 3. Development of selected macroeconomic variables in %.

	DE50	DE60	DE80	DE91	DE92	DE93	DE94	DEF0
Real GDP	0.02	0.13	0.33	-0.01	0.08	0.02	0.01	0.13
Employment	-0.04	-0.02	0.10	-0.01	-0.02	-0.01	-0.04	0.03
Real Wage	0.05	0.07	0.19	0.08	0.07	0.09	0.05	0.12

Note: See Table 1.

5 Operational Phase

5.1 Shock Scenario

Technology Improvement

For the degree of efficiency from wind and solar energy for the post-2030 period, we assume an improvement of 5%. This value is lower than the 10% improvement considered in the investment phase since we state that further large positive changes given an already high level of efficiency are technically limited. For *hydrogen*, we assume a productivity gain of 6% according to Maier 2018, which reflects an improvement based on the power-to-gas approach to hydrogen from 90–96% until 2050.

Investment in Capital Stock

Information on capital stock investment in megawatts for both the *elecrenew* and *hydrogen* industries between 2030 and 2045 is limited to the regions of Hamburg (DE60), Mecklenburg-Western Pomerania (DE80) and Schleswig-Holstein (DEF0). All the numbers are provided by NRL work group 5 “New Markets, Business Models & Regulation” and depend on the Network Development Plan Electricity (“Netzentwicklungsplan Strom”, NEP) by four German transmission system operators—50Hertz, Amprion, TenneT and TransnetBW—published by the German Federal Network Agency (BNetzA).[8] All the entries are converted into mWh via multiplication with 2216 and 4000 full load hours for electricity and H_2, respectively. To compute the numbers given in million USD, we must consider the corresponding prices. The latter amounts to 326.43 (DE60), 319.51 (DE80), and 327.82 (DEF0) USD/mWh for electricity and 0.20 (DE60), 0.21 (DE80) and 0.19 (DEF0) USD/kWh for H_2. These numbers are slightly smaller than the initial values of 346.17 USD/mWh and 0.24 USD/kWh, as we account explicitly for the change in investment prices in transition from one phase to the next. The final entries can be found in Table 4. For technical details, we refer again to Appendix A.2.

Table 4. Investment in the *hydrogen* and *elecrenew* industries between 2030 and 2045 (in million USD).

	DE50	DE60	DE80	DE91	DE92	DE93	DE94	DEF0	RoDE	Total
elecrenew	–	723.38	13,452.85	–	–	–	–	9,443.92	–	23,620.15
hydrogen	–	897.48	5,586.32	–	–	–	–	15,908.05	–	22,391.85

Note: See Table 1. Information on newly installed capacities in gigawatts can be obtained from Table A.1 in the Appendix.

Production Switch

Thus far, we have not accounted for any differences in prices for energy inputs. In a perfect world, substituting out *petrocoalprd* with *hydrogen* (both expressed in the same unit of currency) in the production process poses no problem if the prices of both commodities are equal. Realistically, however, there exists a gap in price between *hydrogen* and *petrocoalprd*. This gap exists since hydrogen is a scarce resource at the start of our simulation period in 2023 and beyond, implying that in this case, the cost structure tightens because a financial burden is added for those industries that switch away from *petrocoalprd* and toward *hydrogen*. The price gap ratio between hydrogen and fossil fuel is given by the (rounded) value of 3.12; i.e., hydrogen is initially 3.12 times more expensive in 2023 than in other years. Once again, we consider the 2023 H_2 price of 0.239 USD/kWh according to Doucet, Düsterlho, *et al.* 2023. From the latter, we also take the average price for natural gas in 2023, given by 0.076 USD/kWh.

8. See https://www.netzentwicklungsplan.de/en for details.

By construction, there is no switching during the investment phase.[9] We assume that after the realized expansion of capital stock and the advancement in technology, the heavy industries of *chemical*, *steel* and *copper* will start to perform the switch within the operational phase, i.e., between 2030 and 2045. The switching rate is set to 99%. This expectation might be seen as ambitious. However, not only is it the preferred (political) target for 2045, but also, for example, according to ICA 2023, carbon dioxide emissions in the *copper* industry might be reduced by 85 to 95% until 2050 since hydrogen (if widely available) could replace natural gas in the production process.

Despite the investment in the capital stock of the *hydrogen* industry, this supply shock does not lead to the price gap being entirely eliminated by the beginning of the phase (Doucet, Düsterlho, *et al.* 2023). We consider subregional price gaps, which are computed as follows. The starting point serves the uniform 2023 H_2 price of 0.239 USD/kWh. Owing to differences in installed capacity, the establishment of the core hydrogen network leads to heterogeneity in individual regionwide price gaps. This heterogeneity then emerges under consideration of the delivered price of the regional composite good hydrogen, i.e., a constant elasticity of substitution (CES) price index, going to that particular destination. Note that goods such as hydrogen are not only taken from home regions but also imported from other subnational regions. The change in the CES price indices is obtained after simulating the investment phase and lies between -9.65% and -17.70%. In contrast to this development, the delivered price changes for *petrocoalprd* are somewhat negligible over the time span of the investment phase after all (price-induced) adjustments have occurred.

Combining the price change for hydrogen with that for fossil fuels, the corresponding subregional price gaps are shown to range from 2.56 to 2.82 at the beginning of the operational phase. We consider these values when computing the corresponding switch ratios, which indicate how much fossil fuel is laid off in production in favor of hydrogen until 2045. We refer to Appendix A.3, where how the production switch is incorporated in EuroTERM is described. Either way, industries facing a wide price gap must overcome this liability regarding the higher input cost of hydrogen relative to fossil fuel when switching.

5.2 Discussion of Results

Effects at the Industry Level

The simulation results for the percentage changes in output (x_{IND}) and prices (p_{IND}) for selected industries and commodities are displayed in Table 5. In addition to the heavy industries and those of *hydrogen* and *elecrenew*, we also explicitly consider the development of the *petrocoalprd*, *manufacturing*, and *construction* industries to obtain a better understanding of the results, which indicate that output in heavy industries declines across all regions. This finding holds, especially for chemical products, where the corresponding industry lays off a large amount of fossil fuels, even holding despite the observation that output in the *hydrogen* and *elecrenew* industries strongly increases due to the amount of investment and higher demand. Hence, the cost-intensive production switch toward hydrogen is likely harmful to the development of heavy industries. Interestingly, the decrease in the regionwide production of *petrocoalprd* ranges between -0.77% (DE94) and -4.58% (DEF0), although in heavy industries, this particular input is laid off entirely. The explanation is that all other nonswitching industries face a deterioration of the corresponding price level, which lowers their input costs. As a consequence, those industries partially absorb *petrocoalprd* being left over owing to the switch to using it as input and, therefore, trigger a feedback effect that leads

9. This is true at least regarding heavy industries. However, we allow for a switch in the *hydrogen* industry, where H_2 completely crowds out fossil fuel. The latter is considered an input factor for the H_2 industry in the initial database. By performing the switch over the investment phase, we ensure that H_2 becomes as close as possible to the green type of hydrogen.

to an increase in the price level. At the end of all adjustments, the percentage change in that particular price level is virtually zero, as seen when inspecting the entries in the antepenultimate row of Table 5. In almost all regions, the *construction* and *manufacturing* industries experience an expansion in production caused mainly by the aforementioned decline in the costs for *petrocoalprd* and increased investment in the capital stock for *hydrogen* and *elecrenew*.

Table 5. 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	-18.74	2.60	-22.43	3.11	-24.35	3.76	-27.50	4.18	-25.96	4.08	-25.16	3.96	-30.02	4.29	-19.69	3.30
Steel	-2.89	0.37	-2.54	0.33	-2.75	0.40	-3.26	0.44	-2.67	0.38	-2.78	0.40	-4.46	0.59	-2.70	0.39
Copper	-1.39	0.18	-0.97	0.13	-2.14	0.31	-3.31	0.38	-3.09	0.37	-3.06	0.37	-3.26	0.40	-2.49	0.33
Hydrogen	659.37	-6.05	281.35	28.10	454.29	-12.34	496.05	-6.03	535.36	-6.07	716.94	-6.05	632.95	-6.42	858.46	-12.60
Elecrenew	20.68	-4.98	367.43	-36.99	82.26	-11.33	12.69	-5.00	13.00	-5.00	13.42	-4.99	24.06	-5.03	59.63	-10.86
PetroCoalOPrd	-2.21	-0.02	-2.68	-0.02	-1.87	-0.10	-3.12	-0.02	-3.51	0.00	-3.82	-0.01	-0.77	0.00	-4.58	0.00
Manufacturing	0.00	0.02	0.80	-0.07	0.85	0.12	-0.08	0.05	-0.11	0.04	-0.09	0.06	0.86	-0.07	0.23	0.11
Construction	0.42	0.02	1.07	-0.07	1.33	0.13	0.46	0.03	0.39	0.02	0.62	0.05	0.43	-0.05	0.93	0.11

Note: See Table 1. All entries indicate the deviation in the variables industry output x_{IND} and price p_{IND} relative to the base values given in %.

The negative effects on heavy industries' output are mitigated by the H_2 price shrinking across all northern German regions. The heavy industries in Mecklenburg-Western Pomerania and Schleswig-Holstein benefit the most given price changes of -12.34% (DE80) and -12.60% (DEF0), which makes them also the preferred suppliers of *hydrogen* distributed via the established core network. An outlier for price development is Hamburg (DE60), where an increase of +28.10% even further worsens the cost structure of the industries participating in the switching process. The *hydrogen* price increasing indicates that Hamburg addresses excess demand for this input good. Hence, H_2 output expansion is not sufficient to match the higher demand caused by the switch. This worsening in the competition for an inexpensive *hydrogen* product then partly explains why the change in GDP in DE60 turns out to be largely negative, despite the investment in *elecrenew* and *hydrogen*, as we discuss below.

Effects at the Regional Level

Table 6 below shows mainly negative effects on regional real GDP, employment, and average real wage. Noteworthy exceptions are, again, Mecklenburg-Western Pomerania and, to some degree, Schleswig-Holstein, with real GDP changes of 0.48% (DE80) and -0.15% (DEF0), respectively, whereas other regions, especially Hamburg (DE60) and Weser Ems (DE94), experience distinct negative effects on income. The reasons for such results are manifold.

Regions DE80 and DEF0 face the largest amounts of investment in *elecrenew* (13.4 versus 9.4 billion USD) and *hydrogen* (5.6 versus 15.9 billion USD) compared with DE60 (with only 0.72 billion and 0.89 billion USD, respectively), DE94 faces no investment, according to Table 4. This development has contributed to a strong expansion in the demand for labor and capital. Indeed, employment increases considerably in DE80 and DEF0 compared with other regions, which face a decline in the numbers of hours worked. The expansion in output produced by the *construction* and *manufacturing* industries is caused mainly by the expansion in the capital stock for *hydrogen* and *elecrenew* in DE60, DE80, and DEF0 (see Table 5). This is true since *construction* and *manufacturing* (among others) provide goods that can be used for investment. More generally, owing to EuroTERM's specification for automatic closure, real investment expenditures at the macro level follow the total change in capital stock, which is reflected by the entries in the fourth row of Table 6. While the increase in investment is massive in DE80 and DEF0, at +18.53% and +6.36%, respectively, two observations are worth mentioning. First, this number does not impact real GDP development in DEF0 positively to a large extent because of an increase in imports from other subregions to Schleswig-Holstein, especially in terms of *hydrogen* and *elecrenew* (needed to conduct the switch), as well as *construction* and *manufacturing* (used to build capacity in the energy source sectors); see the entries in the second-to-last row of Table 6. The percentage change of +0.76% contributes negatively to regional GDP performance. Second, despite investment in *hydrogen* and *elecrenew*, overall real investment expenditure for Hamburg (DE60) declines by -0.43%. This finding can be explained mainly by a deindustrialization effect in the *petrocoalprd*, *chemical*, *steel*, and *copper* industries, i.e., those industries that are affected primarily by costly switches, which face decreases in capital stocks of -2.71%, -22.46%, -2.62% and -1.04%, respectively.

Table 6. Development of selected macroeconomic variables in %.

	DE50	DE60	DE80	DE91	DE92	DE93	DE94	DEF0
Real GDP	-0.27	-0.92	0.48	-0.59	-0.72	-0.52	-1.14	-0.15
Employment	-0.00	-0.23	0.26	-0.11	-0.16	-0.07	-0.26	0.10
Real Wage	0.00	-0.22	0.26	-0.10	-0.16	-0.07	-0.25	0.10
Real Investment Expenditure	1.57	-0.43	18.53	-0.66	-0.73	-0.52	-0.60	6.36
Imports	0.01	-0.23	1.96	-0.36	-0.06	-0.05	-0.55	0.76
Real Household Expenditure	-0.06	-0.51	0.47	-0.27	-0.38	-0.19	-0.57	0.15

Note: See Table 1.

Furthermore, real household expenditures act as a root cause for real GDP and employment development in DE80 and DEF0. The reason for this is that such expenditures rely on high wage bills received on the basis of the largest increase in real wages compared with all other regions according to Table 6. This situation goes hand in hand with increases in the total real household expenditure of +0.47% (DE80) and +0.15% (DEF0). Technically speaking, since expenditure on each good is a linear function of prices and income due to the assumption of a Klein–Rubin consumption function, household expenditure increases with higher earnings from labor via wage bills. Hence, the large amount of investment activity in both regions induces an influx of labor from other regions, which, in turn, fosters household expenditure and, therefore, real GDP on the expenditure side.

In addition, the decrease in energy prices for *elecrenew* and *hydrogen* increases the level of industry production as these types of intermediate goods become less expensive. This situation includes a decrease in prices for fossil fuels such as natural gas and coal (*petrocoalprd*), as the latter is laid off by heavy industries. However, industries that are not entitled to the switch end up offering much more affordable energy products over the entire adjustment process. The effect is more pronounced in regions DE80 and DEF0, which experience an enormous expansion in *hydrogen* output, thus benefitting all remaining nonswitching industries. For example, *manufacturing* and *construction* industries make use of +1.26% (+0.20%) and +2.14% (+1.58%) of *petrocoalprd* input in DE80 (DEF0), respectively.

Overall, only regions such as DE80 and, to a certain degree, DEF0 are less (negatively) affected by the costly switch to *hydrogen* in the production process because of strong investment activity. Alongside price drops in *elecrenew* and *petrocoalprd*, those intermediate goods become more attractive for use as inputs. What follows is net capacity building in the capital stock and labor force, which positively stimulates GDP from the demand side of the economy via higher household income and investment. Regions with little to no investment in *elecrenew* and *hydrogen* up to 2045 do not face a significant decrease in production costs or an improvement in economywide demand.

6 Effects of (De)Regulation

The simulation results presented here are obtained under the assumption that regulatory measures concerning the switching and overall production process are absent. The latter comprises allowances and laws that affect industries' business practices. For producers of hydrogen, investment and operating costs are the greatest barriers to further expansion. Additionally, excessive regulation and bureaucratic complexity (e.g., certification standards, eligible power sources for electrolyzers, and processes for issuing guarantees of origin) slow market growth and hinder investment security (Klaas *et al.* 2024). Although exemptions from grid fees, levies, and taxes, as well as additional revenue opportunities from electricity price compensation and the sale of free emission certificates, can significantly improve the economic viability of green hydrogen production, they do not provide long-term planning security for companies. On the one hand, most exemptions and revenue mechanisms are temporary. On the other hand, the complex implementation of electricity price compensation and the free allocation of emission certificates make it difficult for companies to effectively benefit from these measures in practice.

For users of hydrogen, its high cost and limited availability, as well as lack of infrastructure, are the greatest barriers to widespread adoption. While subsidies and regulatory incentives aim to reduce costs, long-term price stability remains uncertain, making it difficult for industries to plan investments in hydrogen-based solutions. Additionally, inconsistent regulatory frameworks and insufficient transport and storage infrastructure further limit access to hydrogen for industrial users (Klaas *et al.* 2024). The proposed hydrogen core network has the potential to reduce hydrogen users' fears of limited availability. However, high costs, bureaucratic delays, and market risks threaten the success of the hydrogen core network. Unclear financing, slow approvals, and regulatory complexities delay investments and infrastructure rollout. Pricing instability and the risk of monopolization further hinder competitiveness. Without transparent costs, streamlined processes, and a competitive market, the network risks being inefficient and slow to deploy.

Our ability to allow for a 99% switch toward H_2 in production is possible only if the substitution process is not hindered by regulatory measures. In contrast, the results shown in Tables B.1 and B.2 in Appendix B stem from a robustness analysis where we assume that only 50% of fossil fuels can be replaced by H_2 due to regulations being in place. A closer inspection reveals that the overall negative effects at both the industrial and regional levels are mitigated. This dampened impact relative to the unregulated scenario comes as no surprise since a 50% switch is, for those industries involved, approximately half as expensive as is a 99% switch.

Even without any kind of regulatory measures in place, for a 99% switch, we obtain mixed results regarding the development of industry output, regional GDP and overall employment caused by the switch in production toward H_2. While the negative impact on regions experiencing high amounts of investment in hydrogen and electricity from renewable energy, such as Mecklenburg-Western Pomerania (DE80) and Schleswig-Holstein (DEF0), is limited, others, such as Hamburg (DE60) and Bremen/Bremerhaven (DE50), seem not to gain at all from the substitution process. Then, the question arises if there is a possibility for further deregulation that is not concerned with the switching and/or production process, e.g., regulatory measures that directly influence the degree of trade efficiency, i.e., how cost-intensive goods can be traded among regions.

Therefore, we ask the following question: *What the effect of deregulating the northern German H_2 core network be on industry output, prices, and regional macroeconomic indicators?* Examples include a reduction in bureaucratic requirements for maintaining the core hydrogen network or a relaxation in law provisions that might hinder the expansion of the hydrogen core network due to a court ruling against it. We claim that this kind of deregulation makes the trade of hydrogen between the northern German regions via the corresponding core network more efficient and, therefore, reduces the associated CES price index for the tradable hydrogen. The index comprises the regional-weighted delivered price for hydrogen plus an exogenous shock component that resembles a price markup. The latter serves as a proxy for the core network fee ("Netzentgelt").[10]

We assume a decrease in the core network fee of 50% caused by deregulation in the operational phase only. The results are shown in Tables 7 and 8. As before, we report the percentage changes in heavy industry outputs (x_{IND}) for *hydrogen* and *elecrenew* as well as those for the corresponding prices (p_{IND}). In addition, we include information on the percentage change in the CES price index for the delivered H_2 price *with* and *without* deregulation, denoted by $\tilde{p}^I_{H2,REG}$ and $p^I_{H2,REG}$, respectively, where the set REG comprises all northern German NUTS2 regions. We then compute the corresponding differential $\Delta p^I_{H2,REG} = \tilde{p}^I_{H2,REG} - p^I_{H2,REG}$, which describes the additional change in the index given in percentage points caused by further deregulation. Details on the computation of the change in the delivered CES price index conditional on the markup are presented in Appendix A.4.

Table 7. Effects of further deregulation: 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	3.24	-0.39	8.64	-0.96	3.86	-0.51	3.49	-0.48	3.39	-0.48	11.20	-1.38	2.38	-0.28	15.26	-1.93
Steel	-0.19	0.04	0.42	-0.03	0.48	-0.02	0.01	0.03	0.20	0.00	0.67	-0.05	-0.19	0.04	0.73	-0.05
Copper	0.06	0.00	0.33	-0.03	1.61	-0.11	0.26	-0.01	0.83	-0.08	1.40	-0.13	-0.05	0.02	1.75	-0.13
Hydrogen	923.91	-6.12	300.49	36.37	598.30	-12.38	669.70	-6.04	729.35	-6.08	920.91	-6.04	913.40	-6.59	1,069.76	-12.64
Elecrenew	19.30	-4.89	363.13	-37.00	82.44	-10.80	13.69	-4.83	11.52	-4.86	17.00	-4.77	23.98	-4.89	59.71	-10.36
$\tilde{p}^I_{H2,REG}$	-88.76		-91.20		-87.06		-87.33		-87.20		-91.23		-86.84		-94.07	
$p^I_{H2,REG}$	-2.19		-1.57		-3.02		-2.26		-2.04		-2.00		-2.17		-3.94	
$\Delta p^I_{H2,REG}$	-86.57		-89.63		-84.04		-85.07		-85.16		-89.23		-84.67		-90.12	

Note: See Table 1. All entries indicate the deviation in the variables industry output x_{IND} and price p_{IND}relative to the base values given in %. The same applies to the CES index of the delivered price for hydrogen with ($\tilde{p}^I_{H2,REG}$) and without ($p^I_{H2,REG}$) regulations as well as the differential $\Delta p^I_{H2,REG} = \tilde{p}^I_{H2,REG} - p^I_{H2,REG}$ given in percentage points.

The entries in the last row of Table 7 indicate that northern German regions would experience a massive decline in the CES price index for delivered hydrogen compared with the case without deregulation. Hence, substituting *petrocoalprd* with *hydrogen* over the course of the operational phase becomes less costly, which leads to greater output in the vast majority of heavy industries in almost all regions. These observations are mirrored by the development of the macroeconomic indicators shown in Table 8. All regions face a boost in real GDP (except for Weser Ems (DE94)), employment and average real wage. Therefore, we conclude that a switch toward hydrogen in production should be accompanied by deregulation regarding the distribution of that particular intermediate good across regions.[11]

10. It can be shown that this shock is technically equivalent to a taste shift impacting agents' preference for a specific traded good (Wittwer 2022). In our case, the resulting increase in export demand for H_2 can then be interpreted as stemming from the positive impact of deregulation, i.e., an exogenous downward shift in the delivered price. Note that we assume a hypothetical deregulation scenario here since, currently, it is not clear if a hydrogen core network fee (like that for electricity) becomes materialized and how the unknown revenue stemming from it is distributed.

11. As we assume a magnitude of deregulation that leads to a decline in the markup for the delivered price of 50%, we arrive at the overall positive figures reported in Tables 7 and 8. Not surprisingly, sensitivity analysis based on markup changes of less than 50% returns mixed positive and negative results regarding industry production and macroeconomic

Table 8. Development of selected macroeconomic variables in %.

	DE50	DE60	DE80	DE91	DE92	DE93	DE94	DEF0
Real GDP	0.10	0.20	0.99	0.06	0.06	0.27	-0.12	0.77
Employment	0.12	0.15	0.47	0.13	0.14	0.25	0.04	0.50
Real Wage	0.20	0.24	0.55	0.21	0.22	0.33	0.12	0.58

Note: See Table 1.

7 Conclusions

In this study, we investigate the effects of transitioning toward carbon-free industrial production in the heavy industries of chemical, steel and copper in northern Germany until 2045. The simulation results from a large-scale CGE model indicate that investments in the capital stock of the newly established hydrogen industry and the capital stock for producing electricity from the renewable natural sources wind and solar have very little effect on industry output, prices, regional GDP, employment and the average real wage until 2030.

The switching process of substituting petroleum, coal and gas with hydrogen between 2030 and 2045, i.e., after the planned core network for hydrogen distribution between the northern region has supposedly been established, might turn out to be a cost-intensive endeavor for the heavy industries involved. The reason for this is that the price ratio of hydrogen versus inputs from fossil fuel at the beginning of 2030 indicates that the former is approximately three times more expensive than is the latter. This situation will bring about strong negative industrial and regional effects in terms of declining output, prices, GDP, employment and real wages. Exceptions are the regions of Mecklenburg-Western Pomerania and (to a certain degree) Schleswig-Holstein owing to high levels of investment activity, especially with respect to hydrogen capacity, in these regions.

We show that further lowering the degree of regulation can lead to a declining trade price for hydrogen and, therefore, has the potential to outweigh the costly switching process. This situation may reverse the effects of improvements in all indicators under investigation at the industrial and regional levels. We state that, on the basis of our simulations, transitioning toward hydrogen used as the main input poses a challenge in terms of achieving cost-effective production in the absence of deregulation and even higher levels of investment activity than planned at the time of this study.

Key measures to support this transition include streamlining regulations to simplify permitting, shorten approval times, and harmonize rules across regions, thus reducing delays in hydrogen infrastructure projects. Lowering grid fees for renewable electricity used in electrolysis would make hydrogen production more cost-competitive, particularly in northern Germany, where wind and solar energy potential is at a high level. Additionally, expanding financial incentives, such as tax reductions for hydrogen-related investments and increased public–private partnerships, would ease the financial burden on businesses and encourage large-scale implementation. Finally, accelerating infrastructure development is crucial, with investments in hydrogen storage, dedicated pipelines, and integration into existing gas grids needed to ensure efficient distribution and long-term cost reduction.

indicators (not shown here). In these cases, the exogenous downward shift in trade prices is not strong enough to outweigh the cost-intensive switching process in some industries and/or regions.

Our simulations are conducted in the absence of any additional imports of hydrogen from abroad, as the amount of that input already would suffice to establish a (even though costly) certain output level. In addition to attempts to deregulate the distribution process for hydrogen and/or to ensure higher-level investment activity, the question of how imports from foreign sources affect the cost structure of switching industries arises. However, we leave this topic for further research.

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Appendix

A Underlying Key Equations

In the following, we show how the values of shock variables (in percentage terms) x_j^{CAP}, $a_{j,REG}^{FIN}$, $a_{H2,IND,REG}^{INT}$ for $j \in \{H2, ER\}$ and $a_{H2,ORG,REG}^{TRA}$ are numerically computed via key equations based on EuroTERM. Lowercase (capital) letters indicate, in general, percentage changes (levels) in the model variables. The following abbreviations apply. Superscripts FIN, INT, and TRA are linked to a specific technology shock, a, and denote the final industry output, intermediate good and delivered price markup, respectively. CAP and x stand for the value of capital rentals and the corresponding change in quantity, respectively. The *hydrogen* (*elecrenew*) industry IND has the abbreviation $H2$ (ER). $ORG = REG$ holds. Hence, the origin ORG and destination (region) REG of hydrogen trade are limited exclusively to all northern German subregions, which represent the focal points of our investigation. Note that $REG \in \{DE50, DE60, DE80, DE91, DE92, DE93, DE94, DEF0\}$ applies.

A.1 Technology Improvement

$a_{j,REG}^{FIN}$ denotes an all-input-augmenting technical change measuring the level of corresponding productivity and represents 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. $a_{j,REG}^{FIN}$ 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. The latter assumes that the components of production will be used in fixed (technologically preset) proportions since no factor substitutability exists. The composition of demand for primary factors is proportional to the final industry output $x_{j,REG}^{FIN}$. Considering the corresponding price change in primary factor composites, the final output changes in response to adjustments in labor $x_{j,REG}^{LAB}$, capital $x_{j,REG}^{CAP}$ and technology $a_{j,REG}^{FIN}$; i.e.,

$$x_{j,REG}^{FIN} = \psi_{LAB} \cdot x_{j,REG}^{LAB} + \psi_{CAP} \cdot x_{j,REG}^{CAP} - a_{j,REG}^{FIN}, \tag{A1}$$

where $\psi_{LAB} > 0$ ($\psi_{CAP} > 0$) denotes the value share of labor (capital) in primary factor costs, applies. Note that in EuroTERM, a negative value of $a_{j,REG}^{FIN}$ implies a positive percentage change in productivity. According to Equation (A1) above, this leads, ceteris paribus, to a positive stimulus on final industry output $x_{j,REG}^{FIN}$. In our paper, this productivity gain serves as a proxy for the improvement in the degree of efficiency of electrolysis as well as the electricity generation process, as discussed in the main text. In particular, we consider $a_{H2,REG}^{FIN} = -11$ ($a_{H2,REG}^{FIN} = -6$) and $a_{ER,REG}^{FIN} = -10$ ($a_{ER,REG}^{FIN} = -5$) in the investment (operational) phase for all regions of northern Germany belonging to the set REG, where all numerical values resemble percentage changes.

A.2 Increase in Investment

Equation (A1) implies that percentage changes in capital stock $x^{CAP}_{j,REG}$ have a direct effect on $x^{FIN}_{j,REG}$. 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 data, capital rentals rather than stocks are statistically reported. In this paper, we employ both expressions in a synonymous way. As industries rent capital for use in production, we must consider the corresponding rental price of capital. That is, if the capital had been rented out somewhere else instead of being utilized for production, then the rental price of the capital would have been the opportunity cost of the missed income. Then, it follows that we denote r_j as the rental rate, which also stands for the return on equity on the basis of an industry's evaluation of its own capital stock.

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

$$x^{CAP}_{j,REG} = \frac{INV_{j,REG} \cdot r_j}{CAP_{j,REG}} \tag{A3}$$

where the product of the newly installed capital stock and the rental rate allows for the evaluation of additional capital that can potentially be rented out. By putting this in relation to the existing capital stock prior to the shock, we obtain the percentage change in capital rentals from one steady state to the next steady state.

For the investment phase, we assume a uniform rental rate of 3% to hold, which implies that $r_{H2} = r_{ER} = 0.03$. Therefore, we use the rental rate for already existing installations ("Altanlagen") in the *elecrenew* industry as a reference. Since it is not possible to absolutely predict values for the operational phase, we take a conservative view and simply assume that all installed capital stocks in the *hydrogen* and *elecrenew* industries exhibit a uniform rental rate of 1%; i.e., $r_{H2} = r_{ER} = 0.01$ is considered. The investment in the capital stock in both phases given in gigawatts used to compute all corresponding entries in million USD, as described in the main text, is displayed in the following table.

Table A.1. Investment in both phases given in gigawatts.

Investment Phase	DE50	DE60	DE80	DE91	DE92	DE93	DE94	DEF0	RoDE	Total
$INV_{ER,REG}$	0.060	0.085	3.942	1.831	1.831	1.831	1.831	4.423	52.513	68.347
$INV_{H2,REG}$	0.700	0.160	1.315	–	–	–	–	1.412	–	3.587
Operational Phase	**DE50**	**DE60**	**DE80**	**DE91**	**DE92**	**DE93**	**DE94**	**DEF0**	**RoDE**	**Total**
$INV_{ER,REG}$	–	1.0	19.0	–	–	–	–	13.0	–	33.0
$INV_{H2,REG}$	–	1.0	6.0	–	–	–	–	18.3	–	25.3

Note: Data are provided by Bund-Länder-Kooperationsausschuss 2022, 2023, publicly available information online and NRL work group 5 "New Markets, Business Models & Regulation". 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.

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:

$$p^{CAP}_{j,REG} = -1/\sigma \cdot x^{CAP}_{j,REG} \tag{A2}$$

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 a decrease in the price of capital and hence relaxes the cost structure of the industry, which, in turn, leads to greater industry output.

A.3 Production Switch

$a^{INT}_{H2,IND,REG}$ denotes the intermediate technology change regarding *hydrogen* used in industry IND (*chemical*, *steel* and *copper*) 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 *hydrogen* 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 being needed for production and vice versa.

We set $a^{INT}_{PET,IND,REG} = -99$ across all regions and heavy industries during the operational phase, indicating that the demand for *petrocoalprd* is reduced by 99% as the selected industries seek to lay off fossil energy sources used in production entirely. Instead, heavy industries switch to *hydrogen*. The corresponding value for this particular exogenous shock variable is given by

$$a^{INT}_{H2,IND,REG} = \frac{P^{I}_{H2,REG}}{P^{I}_{PET,REG}} \cdot \frac{USE^{INT}_{PET,IND,REG}}{USE^{INT}_{H2,IND,REG}} \tag{A4}$$

where $P^{I}_{z,REG}$ for $z \in \{H2, PET\}$ denotes the CES price index of the regional composite (see below) that holds at the beginning of the operational phase. Hence, the first term in Equation (A4) denotes the price gap ratio for the price for *hydrogen* versus that for *petrocoalprd*. As stated in the main body of the text, at the beginning of the operational phase, we observe that $P^{I}_{H2,REG}/P^{I}_{PET,REG} > 1$ for all regions, indicating that *hydrogen* is much more expensive than is *petrocoalprd*. Note that the regional price gaps narrow in the transition from the investment to the operational phase because the supply shocks described above lead to a negative change in $P^{I}_{z,REG}$ but remain significantly above unity.

Considering a uniform price gap ratio of 3.12 at the beginning of the investment phase, we obtain the ratio for each single region computed via both $p^{I}_{PET,REG}$ and $p^{I}_{H2,REG}$ (which is based on Equation (A5) below) at the beginning of the operational phase stored in the following table.

Table A.2. Price ratio of H_2 versus *petrocoalprd* in levels in all northern German regions.

	DE50	DE60	DE80	DE91	DE92	DE93	DE94	DEF0
$P^{I}_{H2,REG}/P^{I}_{PET,REG}$	2.80	2.73	2.80	2.86	2.85	2.75	2.85	2.65

$USE^{INT}_{z,IND,REG}$ denotes the corresponding delivered value of demand. The latter states how much of the particular intermediate good is used in the production process in IND per REG expressed in million USD and is taken directly from the updated database obtained after the first simulation for the investment phase. According to Equation (A4), the change in the demand for *hydrogen* needed to crowd out *petrocoalprd* depends on the initial price gap ratio and how much *petrocoalprd* is used relative to hydrogen prior to the switch displayed by the second term.

A.4 Markup Reduction

With a focus on *hydrogen*, the percentage change in the aforementioned CES price index denoted by $p^{I}_{H2,REG}$ is computed via the weighted average of the influx of *hydrogen* to the particular region REG times the change in the effective delivered price, i.e., the trading price for *hydrogen* $p^{TRA}_{H2,ORG,REG}$ under consideration of the exogenous shock variable $a^{TRA}_{H2,ORG,REG}$, which measures the change in the markup on the trading price. A negative parameterization of the latter indicates a reduction in the fee for establishing and maintaining a hydrogen core network caused by (further) deregulations, e.g., fewer bureaucratic requirements as discussed in the main body of the text. The percentage change in level for the CES price index $P^{I}_{H2,REG}$ in the operational phase is therefore computed via

$$p^{I}_{H2,REG} = \frac{\sum_{ORG=DEF50}^{DEF0} \left\{ T_{H2,ORG,REG} * \left(p^{TRA}_{H2,ORG,REG} + a^{TRA}_{H2,ORG,REG} \right) \right\}}{\sum_{ORG=DEF50}^{DEF0} T_{H2,ORG,REG}} \tag{A5}$$

where $T_{H2,ORG,REG}$ denotes the value for the traded amount of *hydrogen* shipped between regions, including costs for transportation in million USD. It is also based on information taken from the updated database obtained after the first simulation for the investment phase. Note that we arrive at $\tilde{p}^{I}_{H2,REG}$ as stated in the main body of the text, as we consider $a^{TRA}_{H2,ORG,REG} = -50$. According to Equation (A5), this negative value for this exogenous variable then implies a 50% reduction in the network fee, which makes the shipping of *hydrogen* between regions less cost intensive. This situation leads to a decrease in the CES price index.

B Impact of Regulations

Table B.1. Development of output and prices in selected industries in % in the case of a 50% switch.

	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	-10.32	1.37	-12.43	1.63	-13.65	2.00	-15.99	2.26	-14.96	2.20	-14.39	2.13	-17.51	2.30	-11.13	1.79
Steel	-1.53	0.20	-1.24	0.17	-1.29	0.21	-1.71	0.24	-1.37	0.21	-1.42	0.22	-2.30	0.31	-1.46	0.23
Copper	-0.74	0.10	-0.46	0.07	-0.80	0.15	-1.78	0.21	-1.61	0.20	-1.58	0.20	-1.71	0.21	-1.26	0.19
Hydrogen	384.20	-6.04	235.66	12.68	272.81	-12.62	287.59	-6.01	310.62	-6.04	409.39	-6.03	372.28	-6.38	501.24	-13.22
Elecrenew	19.29	-4.97	368.44	-37.40	81.92	-11.94	10.27	-4.97	11.93	-4.98	8.24	-4.96	21.57	-5.00	59.17	-11.81
PetroCoalOPrd	-1.27	-0.01	-1.47	-0.02	-0.66	-0.11	-1.79	-0.01	-2.00	0.01	-2.15	-0.02	-0.45	0.00	-2.53	-0.01
Manufacturing	-0.09	0.03	0.31	-0.01	0.96	0.12	-0.05	0.05	-0.07	0.05	-0.05	0.06	0.43	-0.02	0.36	0.11
Construction	0.42	0.03	0.99	-0.01	1.39	0.13	0.47	0.04	0.40	0.04	0.68	0.06	0.38	-0.01	1.01	0.11

Note: See Table 1 in the main body of the text. All entries indicate the deviation in the variable industry output x_{IND} and price p_{IND} relative to the base values given in %.

Table B.2. Development of selected macroeconomic variables in % in the case of a 50% switch.

	DE50	DE60	DE80	DE91	DE92	DE93	DE94	DEF0
Real GDP	-0.14	-0.46	0.71	-0.33	-0.39	-0.27	-0.66	0.11
Employment	-0.00	-0.11	0.31	-0.05	-0.09	-0.02	-0.16	0.14
Real Wage	0.02	-0.09	0.33	-0.03	-0.07	0.00	-0.14	0.16
Real Investment Expenditure	0.93	-0.17	19.18	-0.37	-0.41	-0.26	-0.32	6.68
Imports	0.03	-0.08	2.09	-0.14	0.02	0.06	-0.30	0.86
Real Household Expenditure	-0.02	-0.23	0.61	-0.12	-0.19	-0.05	-0.34	0.26

Note: See Table 1 in the main body of the text.