A Forward Calibration Method for New Quantitative Trade Models

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November 8, 2018

Abstract

This article introduces an innovative and flexible dynamic forward calibration method for disaggregated new quantitative trade models, particularly the Eaton and Kortum model, within a computable general equilibrium framework. The model is parameterized based on distinct, consistent future development scenario assumptions about EU climate policy, economic growth, energy efficiency, the electricity mix and structural change (sectoral shifts) derived through a complex scenario-creation process. The model equations and the scenario assumptions are implemented as side constraints of an optimization problem minimizing the difference between historical and targeted technology levels (sectoral productivities). This method is combined with input-output data disaggregation methods to separate Northwest Germany from the rest of Germany and to represent different power generation technologies. This setup enables the comparison of alternative regional sustainability-oriented long-term policy pathways. Despite the importance of the policy pathways envisaged by Northwest Germany's governments to society, they have limited macroeconomic effects in the simulations. In contrast, the future development scenario assumptions significantly affect European economies, particularly via the EU climate policy costs that drastically increase towards 2050. If Northwest Germany's energy transition fails, then its climate policy costs will increase extraordinarily.

JEL Classifications: C68, F17, L16, O40

Keywords: EU climate policy; forward calibration; regional model; structural estimation; new quantitative trade theory

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1 Introduction

This article focuses on the heterogeneity of climate policy over time and space. By taking both dimensions into account and introducing a novel dynamic forward calibration method for *new quantitative trade (NQT)* models, this work provides guidance for policy makers with a sustainability-oriented long-term perspective.

In the time dimension, climate change is a long-term phenomenon that requires sustainable long-term climate action. Accordingly, the European Union (EU) *Roadmap for moving to a competitive low carbon economy in 2050* (EU Commission, 2011) envisages a vast reduction in greenhouse gas emissions, which is reflected by an 80% reduction in CO_2 emissions and a 90–100% share of renewable energies in power generation by 2050 in the following analysis. The design of such long-term policies, however, requires the formulation of intermediate policy measures through time towards the targeted end point subject to uncertainty in economic growth, structural change and energy efficiency. This includes Germany's energy transition with a nuclear phase out in 2022. To this end, an elaborated calibration method will be introduced that matches the model with distinct, consistent macroeconomic *future development scenarios* that have been derived via a complex scenario-creation process (Gausemeier et al., 1998; Gausemeier and Plass, 2014; Blank et al., 2016).

In the space dimension, climate policy has both a global and a regional scope. On the one hand, greenhouse gas emissions affect the world's climate irrespective of where they have been emitted, turning the climate into a global public good. Furthermore, countries and subnational regions are globally connected via international trade. On the other hand, climate mitigation costs can substantially vary between and within countries. Consequently, region-specific policies and mitigation efforts need to be integrated in the supraregional policy system to achieve an efficient solution. To study regional heterogeneity within the European Union Emissions Trading System (EU ETS), a static regionally and sectorally disaggregated NQT model (Pothen and Hübler, 2018) will be dynamically calibrated to *future development scenarios* to simulate region-specific *policy evaluation scenarios*. These scenarios have been derived from policy strategies envisaged by the subnational governments of Northwest Germany (NWG) (Faulstich et al., 2016).

The implementation of the *future development scenarios* indicates that NWG significantly benefits from productivity increases in the rest of Germany (ROG) and Europe via international trade. Such implementation yields small welfare losses for NWG induced by the EU climate policy until 2040, whereas the losses will drastically increase towards

2050. The results show that energy-saving structural change, energy efficiency improvements and an assumed quasi-100% renewables share can drastically reduce these losses from 16% caused by a failed energy transition to 0.5%; they can also (over)compensate for the additional climate policy costs of reasonably higher economic growth. The simulations of the NWG-specific *policy evaluation scenarios* indicate that the enhanced utilization of onshore wind power and rooftop photovoltaics (PVs) slightly reduces NWG's gross domestic product (GDP), whereas the enhanced utilization of offshore wind power and free-field PVs slightly raises NWG's GDP (approximately $\pm 0.1\%$). Thus, despite their potential importance for the local society and economy, the decisions of NWG's governments on wind and solar power technologies and their locations create limited welfare or other macroeconomic effects for NWG and other European regions.

NWG encompasses the German federal states of Lower Saxony, Hamburg and Bremen. With its relatively low population density and long shorelines, NWG is a prime location for onshore and offshore wind power in Germany. In 2011, wind turbines generated 15.1% of NWG's electricity compared to 6.5% in the rest of the country. As a consequence, Lower Saxony's climate mitigation costs, measured as welfare losses, are substantially smaller than those in the rest of Germany today (Pothen and Hübler, 2018). For 2050, Faulstich et al. (2016) develop scenarios in which NWG's electricity is exclusively generated by renewable energies. Against this backdrop, the following analysis considers NWG's economic development until 2050 in comparison with that of other countries.

Conventional computable general equilibrium (CGE) models are standard instruments for quantifying the economic effects of climate policy. For this purpose, CGE models are often calibrated to externally given scenarios of the future world economy in a recursive-dynamic way, a process dubbed forward calibration (e.g., Böhringer et al., 2009). Structural change from energy-intensive manufacturing industries towards service sectors (Herrendorf et al., 2014) and energy efficiency improvements within sectors, however, change the economic situation faced by policy makers and lead to lower mitigation costs, irrespective of policy intervention.

Incorporating these aspects, this article introduces a transparent forward calibration method that allows the modeler to parameterize a static CGE model based on a set of scenario assumptions about climate policy, economic growth, energy efficiency, the electricity mix and structural change (sectoral shifts). The starting point is an NQT model, such as the Eaton and Kortum (2002)-type model presented by Pothen and Hübler (2018).[1]

[1] In general, the method can also be adapted to conventional CGE models.

Our NQT model combines trade-theoretic microfoundations (Eaton and Kortum, 2002; Caliendo and Parro, 2015) with the complex production and consumption structure of CGE models (Böhringer et al., 2003). Due to the focus on Ricardian comparative advantages and the explicit microfounded representation of technological change (productivity gains), this model type is predestined to be used for the forward calibration. In contrast to standard CGE models, the model calibration for NQT models requires the structural estimation of a gravity trade model. The novelty of the method described in this article is the prescription of the static exogenous technology parameter of the Eaton and Kortum (2002) model to the future to match given scenario assumptions.

Compared to the approaches prevailing in the literature, this method has three advantages. First, it allows the modeler to jointly impose constraints on both economic growth driven by regional productivity improvements based on the Eaton and Kortum trade theory and structural change among the agriculture, manufacturing and service sectors. Calibrating a model to scenarios of this complexity in a trial-and-error fashion would be prohibitively time-consuming. Second, once the forward calibration process has been implemented, the model can easily be calibrated to a variety of different scenarios. Third, the forward calibration process can be described and replicated exactly, which creates transparency.

Five scenarios of economic growth, structural change, climate policy and other factors until 2050 illustrate the forward calibration process. These scenarios, denoted *future development scenarios (FDSs)*, represent a combination of distinct and internally consistent assumptions about the evolution of the world economy with a focus on NWG. The scenarios have been developed by the interdisciplinary project consortium Nachhaltige Energieversorgung Niedersachsen (NEDS, Sustainable Energy Supply Lower Saxony).[2] Within NEDS, the forward calibration process bridges the gap between the local technologically and politically feasible policy options and the EU climate policy goals.[3]

For each of the five FDSs, three *policy evaluation scenarios (PESs)* are assessed. These PESs represent policy options formulated by NWG's authorities and mainly concern

[2]NEDS studies possible transition pathways towards sustainable electricity supply in NWG, `https://www.neds-niedersachsen.de/`.

[3]Within the project consortium, criteria for quantifying sustainability have been compiled, and distinct, internally consistent future development scenarios have been developed via the complex scenario-creation process of Gausemeier et al. (1998) and Gausemeier and Plass (2014). The scenarios have been evaluated in a number of studies within different scientific disciplines to quantify their implications for selected sustainability criteria. Based on these scenarios, the effects of NWG's policy options are evaluated. Within the project consortium, the results are compared in a multiple-criteria decision analysis (MCDA; Belton and Stewart, 2003; Greco et al., 2016). For an overview, see Blank et al. (2016) and Schwarz et al. (2017).

NWG's electricity mix regarding the shares of onshore and offshore wind power as well as free-field and rooftop photovoltaics (PVs). Thus, the PESs scrutinize the interplay between subnational policies and global climate policy.

The forward calibration process is implemented in three steps. In the first step, the model parameters are estimated based on benchmark data for 2011. Following Pothen and Hübler (2018), the estimation approach is formulated as a log-multiplicative gravity model that jointly quantifies three parameter sets of the Eaton and Kortum (2002) model: the sectoral absolute productivities, the iceberg trade costs between regions, and the sector-specific trade elasticities.

The forward calibration process of the FDS constitutes the second step. Twelve parameters are calibrated based on assumptions about economic and population growth, structural change, autonomous energy efficiency improvements (AEEIs), climate policies inside and outside of the EU and the electricity mix of *NWG*. The forward calibration method determines a unique set of sectoral absolute productivities required for the Eaton and Kortum (2002) model that constitute a model equilibrium and fulfill the constraints imposed by the scenario assumptions. Changes in the sectoral productivities represent technological progress, which enhances economic growth and affects structural change via the relocation of production towards more productive sectors. Furthermore, the forward calibration determines the CO_2 price in the EU ETS and the implicit marginal CO_2 abatement costs in non-ETS sectors. In the third step, the PESs representing policy options for *NWG* are incorporated and evaluated.

The article continues as follows. Section 2 explains the theory underlying the model and the forward calibration. Section 3 details the static calibration and forward calibration processes as well as the policy evaluation scenarios. Section 4 discusses the calibration and simulation results. Section 5 concludes the article.

2 Methodology

2.1 Overview

The purpose of the forward calibration process is to parameterize a complex general equilibrium model of trade and climate policy (such as that in Pothen and Hübler, 2018) based on scenarios representing economic developments over the course of several decades. These scenarios are denoted *future development scenarios (FDSs)* throughout the article and incorporate a diverse set of assumptions concerning economic growth and structural change, energy intensities, and climate policy.

The forward calibration proceeds as follows. Changes in factor endowments are assumed to be exogenous. The growth (or decline) of the labor force is taken from the literature, and the growth of the capital stocks is closely related to the economic growth rate (see section 2.3). Other assumptions, for instance, those about autonomous energy efficiency improvements (AEEIs) or efficiency gains in electricity generation, are also part of the scenario definition. Iceberg trade costs and households' utility functions are held constant. Under these assumptions, economic growth and structural change are driven solely by technological progress.

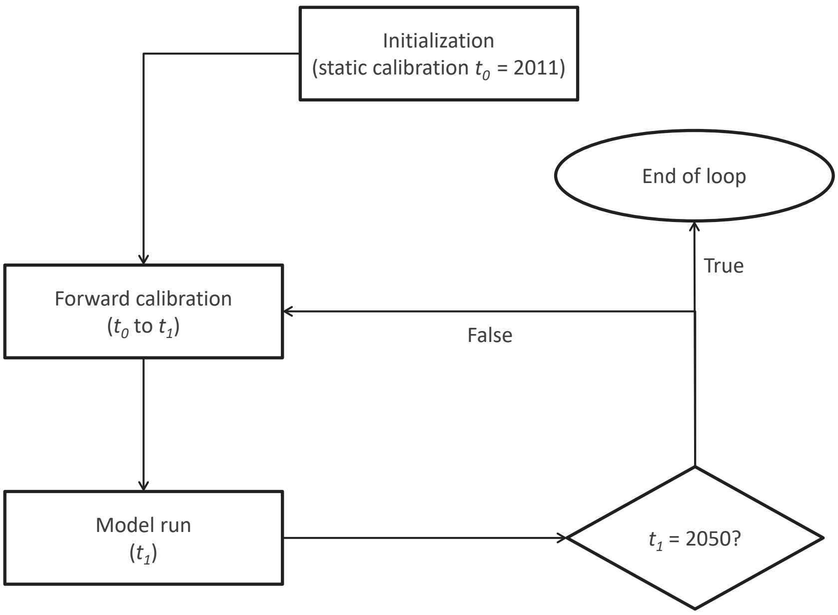
The state of a country's technology is quantified by the country's sector-specific absolute productivities. The forward calibration process estimates the change in these productivities between the years t_0 and t_1 by sector. The set of new productivity parameters must comply with two types of restrictions. First, the set must constitute an equilibrium of the general equilibrium model. Second, the set must comply with the restrictions implied by the assumptions about the economy in t_1. Among the potentially large set of productivity parameters that fulfill these restrictions, one is selected by minimizing the sum of squared differences between old and new productivities.

In addition to the forward calibration itself, the model is used to quantify the economic effects of policy strategies for NWG under the *policy evaluation scenarios (PESs)*. The policy strategies reflect differences in NWG's electricity mix, i.e., the composition of technologies used to generate electricity. We consider, for instance, the shares of onshore and offshore wind power in electricity generation, which can be influenced reasonably well by the federal states. The PESs are implemented as model simulations that are run between the steps of the forward calibration process.

Notably, the forward calibration process is recursive dynamic. The process is conducted in four steps for the years $t \in T = \{2020, 2030, 2040, 2050\}$. Neither firms nor households have perfect foresight, which implies that the policy effects of the PESs are not anticipated. Whereas model variables, such as GDP or CO_2 emissions, change in response to the PESs, growth rates as well as other assumptions about the FDSs remain the same under all PESs.

We distinguish between five FDSs (subsection 3.2) and three PESs (subsection 3.3), where the third PES serves as the baseline. The PESs are examined for each FDS, leading to 15 scenarios. Figure 1 illustrates how the forward calibration process and the model simulations for each combination of FDS and PES are conducted.This process is implemented as a loop that starts in 2011 with the static calibration of the model based on historical data (section 3.1). Then, the forward calibration process parameterizes the model based on the assumptions for 2020. Thereafter, the simulations for 2020 are conducted in accordance with the PES. This process is repeated until 2050.

Figure 1
The forward calibration process



2.2 Static model

The model setup draws on the static *Ricardian new quantitative trade (NQT)* model by Pothen and Hübler (2018) building on the theory of Eaton and Kortum (2002, henceforth EK) and the numerical implementations by Alvarez and Lucas (2007), Caliendo et al. (2014) as well as Caliendo and Parro (2015).

The model distinguishes between sectors indexed $i \in I$ or $j \in I$ and regions denominated $r \in R$ or $s \in R$. r generally represents the supplying or exporting region, while s denotes the importing region. The regions encompass individual countries, groups of countries and, in the case of Germany, two subnational regions: Northwest Germany (NWG) and the rest of Germany (ROG). The former region includes the federal states of Lower Saxony, Hamburg, and Bremen (whereas Pothen and Hübler (2018) excluded Hamburg and Bremen). The latter region encompasses all other German federal states. Tables A1 and A2 in appendix A list the 18 sectors and 19 regions considered in the model.

In each region, a representative consumer (including private and public consumption) absorbs an aggregate of all sectoral goods and supplies her exogenous endowments of labor and capital inelastically to receive factor income that exactly matches her consumption expenditures. Likewise, in each sector of each region, a representative producer (firm) combines aggregate (intermediate) goods and primary factors to produce the sector-specific output. His production technology is modeled with nested constant elasticity of substitution (CES) production functions, which have proven to be well-suited for studying energy and climate policy (van der Werf, 2008). A technology-specific representation of power generation (Sue Wing, 2008; Böhringer and Rutherford, 2008) is implemented in the electricity sector to allow for endogenous adjustments of the electricity mix (including renewable energies) in response to policy shocks and technological development. Constant returns to scale, perfect competition and zero profits occur in all markets.

Following the EK theory, each representative firm produces a continuum of differentiated varieties of the sector's good. Varieties are traded internationally. Individual varieties from different regions are perfect substitutes. Thus, consumers and firms purchase a variety from the region that supplies it at the lowest cost.[4] These costs are determined by three factors: the per-unit input costs of production, trade costs (tariffs as well as nontariff barriers) and the productivity of manufacturing a variety.

The productivity consists of two components: a sector-specific deterministic absolute productivity, denoted $T_{i,r}$, representing the general productivity of the sector and a variety-specific probabilistic productivity drawn from a Fréchet distribution.

The varieties are combined into a Dixit-Stiglitz aggregate serving as a final consumption good or an intermediate good. Aggregates are not traded internationally. This setup allows the modeler to derive tractable expressions for a sector's price index ($P_{i,s}$) and the trade share ($\pi_{i,r,s}$), i.e., the fraction of good i that region s purchases from region r.

Trade flows react to policy or technology shocks at the intensive and extensive margins. Both the amount and the composition of varieties change in response to such shocks. International trade forces sectors to specialize in the production of varieties for which they have the highest productivity, leading to endogenous Ricardian specialization (Ricardian Selection; Finicelli et al., 2013), which improves energy and CO_2 productivities compared to autarky.

While the macroeconomic effects of the EK model are reproducible by the canonical Armington (1969) model of trade (Arkolakis et al., 2012), the EK model possesses microfoundations that appear particularly convincing for energy-intensive upstream goods.

[4] In reality, the steel sector, for example, distinguishes between 3,500 types (grades) of steel (World Steel Association, 2017). Once a specific type has been selected, it is irrelevant whether the type was produced in the United States, China or elsewhere.

Furthermore, the close connection between theory and empirics in the EK model enables innovative approaches for calibrating the model (e.g., Eaton and Kortum, 2002; Simonovska and Waugh, 2014; Caliendo and Parro, 2015).

2.3 Forward calibration

The absolute productivity $T_{i,r}$ represents the sector- and region-specific productivity (efficiency) of using the input bundle, consisting of both primary factors and intermediate inputs. The forward calibration process quantifies a unique updated set of absolute productivities in year t_1, which we denote as $\widetilde{\mathbf{T}} := \widetilde{T}_{i,r}, \forall r \in R, \forall i \in I$. Throughout this article, a tilde designates model variables determined by the forward calibration process. The set of new absolute productivities $\widetilde{\mathbf{T}}$ has to comply with two types of restrictions. First, the set must constitute an equilibrium of the NQT model. Second, $\widetilde{\mathbf{T}}$ must comply with the restrictions implied by the assumptions about the economy in t_1.

The model is in equilibrium if a set of 13 equations is simultaneously fulfilled (see Pothen and Hübler, 2018, table 1). The system of equations (1) summarizes these conditions as a function of the absolute productivities in all sectors and regions ($\widetilde{\mathbf{T}}$).

$$\mathbf{F}(\widetilde{\mathbf{T}}) = \mathbf{0} \tag{1}$$

The following restrictions are implemented in the forward calibration process to ensure that the assumptions of the FDS are fulfilled. The first restriction (equation 2) pins down economic growth, i.e., it matches the increase in real GDP between t_0 and t_1 by region with an exogenous growth rate g_r^{GDP}.

Y_r and $\widetilde{Y}_r$ denote the nominal income of region r in t_0 and t_1, respectively. c_r^C and $\widetilde{c}_r^C$ are the corresponding consumer price indices in t_0 and t_1, respectively. We correct for the exogenous current account deficit Δ_r, which is part of households' income but not part of GDP. This deficit is held constant throughout the forward calibration process and the policy evaluations.

$$\frac{\left(\frac{\widetilde{y}_r + \Delta_r}{\widetilde{c}_r^C}\right)}{\left(\frac{y_r + \Delta_r}{c_r^C}\right)} = g_r^{GDP} \tag{2}$$

The second and third sets of restrictions concern structural change. Equation (3) restricts the change in the share of the agricultural sector ($AGRI$) in region r's economy. $V_{i,r}$ is the value added used by sector i in r. We assume that the share of $AGRI$ in overall value added changes between t_0 and t_1 according to the exogenous parameter β_r^{AGRI}.

$$\frac{\left(\frac{\widetilde{V}_{\text{AGRI},r}}{\sum_i \widetilde{V}_{i,r}}\right)}{\left(\frac{V_{\text{AGRI},r}}{\sum_i V_{i,r}}\right)} = \beta_r^{AGRI} \tag{3}$$

Changes in the share of the service sectors ($TRNS, CONS$, and $SERV$) in value added are implemented by equation (4) and determined by the exogenous parameter β_r^{SRV}.

$$\frac{\left(\frac{\sum_{srv} \widetilde{V}_{srv,r}}{\sum_i \widetilde{V}_{i,r}}\right)}{\left(\frac{\sum_{srv} V_{srv,r}}{\sum_i V_{i,r}}\right)} = \beta_r^{SRV} \tag{4}$$

The FDSs also encompass assumptions about the electricity mix of NWG. Let $Q_{g,r}$ denote the generation of electricity by technology g in region r in gigawatt hours (GWh), and β_g^{TEC}, the share of technology g in NWG's electricity mix that is specified under the FDS. Then, restriction (5) ensures that the targeted share is achieved.

$$\frac{\widetilde{Q}_{rnw,NWG}}{\sum_g \widetilde{Q}_{g,NWG}} = \beta_g^{TEC} \tag{5}$$

The absolute productivities are defined by sector and do not differ between generation technologies in the electricity sector. An alternative set of endogenous variables is needed to enable the forward calibration process to fulfill restriction (5). It is not possible to employ an endogenous subsidy for this purpose because several (or all) fossil fuel-dependent technologies are phased out at the end of the period under consideration. Because the model combines generation technologies with a CES function, the activity level of a technology cannot reach zero. Therefore, the input share of each technology in the electricity sector in NWG is considered an endogenous variable, namely, $\widetilde{\alpha}_{g,r}^{TEC}$, and determined by the forward calibration process.

Two additional restrictions are necessary to determine the endogenous input shares of technology g in NWG. First, by definition, the shares have to add up to unity ($\sum_g \widetilde{\alpha}_{g,NWG}^{TEC} = 1$). Second, the change in the overall costs of the electricity generation is fixed to an exogenous value to avoid unreasonable generation costs.

The electricity sector is treated differently than the other industries in the forward calibration process. The absolute productivities of this sector are held constant ($\widetilde{T}_{\text{ELEC},r} = T_{\text{ELEC},r}$). All productivity changes in electricity sectors are determined by the exogenous productivity changes in the power generation technologies (g_g^{TEC}).

The parameters $\bar{L}_r$ and $\bar{K}_r$ represent the labor and capital endowments, respectively.

The former is taken directly from the data. The evolution of the latter is quantified as follows. Following the Solow model, it is assumed that consumers save a constant fraction of their income and that these savings are invested in their region of residence. Gross investment thus grows proportionally to GDP at the exogenous rate g_r^{GDP}.

Supraregional climate policy constraints are calibrated within the forward calibration process and do not require additional restrictions. These constraints include the number of allowances and the corresponding total CO_2 emissions in the EU ETS sectors ($E\bar{T}S$), which particularly cover energy-intensive industries and power generation. Furthermore, the constraints include the implicit marginal CO_2 abatement costs outside of the EU ETS sectors ($P_{i,r}^{CO2}$), the share of freely allocated emissions in the EU ETS ($\alpha_{i,r}^{fa}$) and the autonomous energy efficiency improvements between t_0 and t_1 ($g_{i,r}^{AEEI}$).

In the regions participating in the EU ETS, an implicit endogenous carbon tax is introduced to regulate emissions not covered by the EU ETS. This tax reflects the marginal abatement costs outside of the EU ETS, representing any measures that reduce CO_2 emissions in non-ETS sectors or in the domain of final consumption to achieve the overall emissions target. This approach is in line with the EU legislation aiming to reduce emissions not considered by the EU ETS (EU Commission, 2011, 2014).

The increases in the prices of the primary energy carriers coal ($COAL$), natural gas ($NGAS$), and crude oil ($CRUD$) are fixed (at $\widetilde{P}_{i,r}^{PEC}$) depending on the FDS.[5]

The restrictions (2) to (5) reflect assumptions about economic growth and structural change, while the system of equations (1) represents the model equations. The forward calibration process determines sets of productivities $\widetilde{\mathbf{T}}$ that simultaneously fulfill the restrictions. A large number of such combinations of $\widetilde{T}_{i,r}$ may exist. To find a unique set of absolute productivities $\widetilde{\mathbf{T}}$, the sum of squared differences between $\widetilde{T}_{i,r}$ and $T_{i,r}$ is minimized for each period.

$$\min_{\widetilde{T}_{i,r}} \sum_{i,r} \left(\widetilde{T}_{i,r} - T_{i,r}\right)^2 \qquad (6)$$

Lower bounds of $\widetilde{T}_{i,r} \geq T_{i,r}$ are set to avoid extreme changes in absolute productivities and, thereby, implausible results. These lower bounds imply that sectoral technology levels do not decline over time.[6] A country's overall productivity level can nevertheless

[5]The output and thereby the CO_2 emission of the primary energy carrier sectors in NWG and the ROG tend to exhibit high sensitivity in the forward calibration process. To avoid unrealistically large changes, the sales of these sectors are capped at their 2011 values.

[6]In a few cases, this restriction has been relaxed in the forward calibration process to find a feasible solution by allowing sectoral productivities $\widetilde{T}_{i,r}$ to fall by up to 5% of their previous levels ($T_{i,r}$).

fall if its sectoral composition shifts from high-productivity activities (e.g., manufacturing) to low-productivity activities (e.g., services).

The forward calibration process is implemented as a nonlinear programming problem in the General Algebraic Modeling System (GAMS; Bussieck and Meeraus, 2004) and solved by using the CONOPT algorithm (Drud, 1985). The absolute productivities in t_0 are used as starting values for the forward calibration process.

3 Calibration

3.1 Static model

The following subsections describe static and dynamic model calibration to data.

The static calibration of the model for 2011 uses the same approach as that in Pothen and Hübler (2018). A log-multiplicative gravity model is employed to estimate three sets of parameters simultaneously: the iceberg trade costs, the sectoral absolute productivities ($T_{i,r}$), and the shape parameters of the Fréchet distribution, which correspond to the trade elasticities in the model (Arkolakis et al., 2012). Constraints representing the goods market clearing conditions ensure that the parameter estimates constitute an equilibrium of the model (Balistreri and Hillberry, 2007; Balistreri et al., 2011).

Input-output data required to calibrate the model are taken from the Global Trade Analysis Project (GTAP) database, version 9 (Aguiar et al., 2016). The GTAP also provides information on taxes, tariffs, and capital stocks. Bilateral distances and other country characteristics are taken from the CEPII GeoDist database (Mayer and Zignago, 2011) as well as from de Sousa (2012). The elasticities of substitution in the utility and production functions stem from the MIT Emissions Prediction and Policy Analysis (EPPA) model (Paltsev et al., 2005). Employment data, which are required to quantify labor endowments, are taken from the International Labor Organization's global employment trends report (ILO, 2014). These data are corrected for human capital by using the index of human capital per person from the Penn World Tables 9.0 (Feenstra et al., 2015).

Following the regional policy strategies, the electricity supplies of the three Northwest German federal states are studied jointly. Therefore, the states are represented as one model region (NWG) by adding Hamburg and Bremen to the disaggregated model of Lower Saxony of Pothen and Hübler (2018). The results of the structural estimation are presented in tables B1 and B2 in appendix B. Despite the different regional disaggregations, the estimation results are very similar to those of Pothen and Hübler (2018).

3.2 Future development scenarios

The future development scenarios (FDSs) comprise macroeconomic assumptions and political conditions defined at higher regional or jurisdictional levels, i.e., Germany, the EU or world regions. These assumptions are exogenous to the governments in NWG. The following paragraphs describe the required data that will be used to implement the FDSs as explained later in this subsection.

A set of twelve parameters are employed in the forward calibration process. These parameters are either implemented directly or enforced by restrictions (2) to (5). Table 1 presents the parameters, their descriptions and the sources of their values.

For each parameter used in the forward calibration process, there are either one or two configurations. In the case of economic growth, for instance, we distinguish between high-growth and low-growth configurations. The only exception is the electricity mix of NWG, which is taken from the Integrierte Netz und Energiemarkt simulation energy dispatch model (INES; Rendel, 2015). The combinations of parameters and scenarios are shown in table 2.

Macroeconomic assumptions for NWG and the ROG are generally based on the study by Faulstich et al. (2016) for the Lower Saxony Ministry of the Environment, Energy, Construction, and Climate Protection (Niedersächsisches Ministerium für Umwelt, Energie, Bauen und Klimaschutz). This report, which has been compiled in a predecessor project of NEDS, develops scenarios for sustainable electricity supply in NWG in 2050. For the other model regions, macroeconomic assumptions are generally based on the International Energy Agency's 2015 World Energy Outlook (henceforth WEO; IEA, 2015).

Assumptions about economic growth are taken from Faulstich et al. (2016, p. 24) for NWG and the ROG. These assumptions include an average growth rate of 0.7% until 2050. This rate is very low compared to that for the WEO and the EU Roadmap 2050 (EU Commission, 2011, 2016) and does not take into account the fact that growth rates are likely to slow down over the next few decades. Therefore, in the high-growth configuration, the German regions' growth rate starts at 1.3% per year and declines to 1.0% per year. In the low-growth configuration, it starts at 0.6% and declines to 0.3%. For the other model regions, the growth rates of the WEO (IEA, 2015, p. 37) until 2040 are used in the high-growth configuration. These growth rates range from an average of 0.8% in Japan to 6.5% in India. For 2040 to 2050, the same growth rates as those for 2030 to 2040 are applied. In the low-growth configuration, the WEO's growth rates are reduced by 50%.

Table 1
Parameters of the forward calibration

#	Parameter	Description	Main data sources	Scenario-dependent
1	g_r^{GDP}	Growth rate of GDP	Faulstich et al. (2016); IEA (2015)	Yes
2	β_r^{AGRI}	Change in the share of agriculture in value added	Faulstich et al. (2016); IEA (2015)	Yes
3	β_r^{SRV}	Change in the share of services in value added	Faulstich et al. (2016); IEA (2015)	Yes
4	$E\bar{T}S$	European emissions reduction goals	EU Commission (2011, 2014)	No
5	$\alpha_{i,r}^{fa}$	Share of freely allocated allowances in the EU ETS	Simplification of EU Commission (2018)	No
6	$P_{i,r}^{CO2}$	Implicit CO_2 price in sectors outside the EU ETS	IEA (2015)	No
7	$\bar{L}_r$	Labor endowments	United Nations (2015)	No
8	$\bar{K}_r$	Capital stocks	Computed based on GTAP data and growth rates	Yes
9	$P_{i,r}^{PEC}$	Prices of primary energy carriers	Similar to IEA (2015)	Yes
10	g_g^{TEC}	Productivity change in generation technologies	Schröder et al. (2013)	No
11	$g_{i,r}^{AEEI}$	Autonomous energy efficiency improvements	AG Energiebilanzen (2015), Bundesregierung (2010)	Yes
12	β_g^{TEC}	Share of technology g in electricity generation (NWG only)	INES Model (Rendel, 2015)	Yes

Assumptions about structural change are based on the WEO (IEA, 2015, p. 39), which expects the share of agriculture in GDP to decline in developed and developing countries (up to an almost 10% reduction in India). The shares of the industry sector also decline in most regions. For NWG and the ROG, it is assumed that either no structural change occurs (Faulstich et al., 2016, see Annex S.4) or the share of agriculture declines by 0.5% and the share of services increases by 4% between 2011 and 2050.

The CO_2 emissions reduction goals for the EU until 2030 have already been codified. In the EU ETS, emissions are to be reduced by 21% by 2020 and by 43% by 2030 compared to 2005 levels. Non-ETS emissions must be reduced by 10% by 2020 and by 30% by 2030, again compared to 2005 (EU Commission, 2014). Furthermore, the European Commission intends to reduce greenhouse gas emissions by 60% by 2040 and by 80% by 2050 compared to 1990 levels (EU Commission, 2011).

The scenarios developed in the NEDS project concentrate on CO_2 emissions.[7] The reduction goals for the EU ETS sectors are more ambitious than those for the non-EU ETS sectors. By 2050, Europe's CO_2 emissions decline by 80% vis-à-vis their levels in 1990, in line with the EU Roadmap 2050 (EU Commission, 2011). The sectors covered by the EU ETS experience a larger emissions reduction (95% vis-à-vis 1990), while the non-ETS sectors account for the remaining reduction. The fraction of freely allocated allowances in the EU ETS ($\alpha_{i,r}^{fa}$) declines to zero by 2020, a simplification of EU Commission (2018).

The assumptions about CO_2 prices outside of the EU follow the WEO 450 scenario (IEA, 2015, p. 42). This scenario assumes that CO_2 prices in high-income nations, such as the United States or Japan, will rise to 140 US$ per ton by 2040. In some industrializing countries, such as China, they are assumed to reach 125 US$ by the same year. We assume that the CO_2 price will rise to 180 US$ by 2050 in all non-European regions that are subject to carbon pricing.

Changes in labor endowments are quantified based on projections by the UN World Population Prospects (United Nations, 2015, medium variant). These changes are calculated by using demographic trends for the overall population as well as the share of the population between the ages of 15 and 59.

The evolution of capital stocks corresponds to that of GDP. Gross investment grows proportionally to GDP at the exogenously given rate g_r^{GDP}, with a depreciation rate of 6% (similar to GTAP), such that the previously discussed economic growth rates are achieved.

[7]The EU climate policy encompasses all greenhouse gases (e.g., methane or nitrous oxide), whereas the utilized GTAP data only contain information on CO_2 emission. By restricting our simulations to CO_2 emission, we implicitly assume that the other greenhouse gases are reduced proportionally to CO_2.

The prices of primary energy carriers (crude oil, natural gas, and coal) exhibit two configurations. In the first one, all primary energy carrier prices are assumed to remain unchanged between 2011 and 2050. In the second one, coal prices rise by 50%, natural gas prices by 40%, and oil prices by 60% between the beginning and the end of the period. These numbers are comparable to those assumed by the WEO in the 450 Scenario and Current Policies Scenario (IEA, 2015, p. 47).

Changes in the electricity generation technologies' efficiency are based on the cost estimates until 2050 by Schröder et al. (2013). We use the reduction in investment costs as a proxy for the improvements in (economic) efficiency.

The electricity mix of NWG is provided by the INES electricity dispatch model (Rendel, 2015) within the project consortium. The CO_2 prices generated by our model serve as inputs to the INES model, creating a feedback loop between the model and the forward calibration process. Because the CO_2 price is not sensitive to changes in the electricity mix of NWG, one iteration is sufficient for the models to converge such that no hard link between the models is required.

The autonomous energy efficiency improvements are quantified based on German data. For a pessimistic scenario, an annual improvement of 1.37% is assumed, which declines to 1.1% per year between 2040 and 2050. The former number reflects the historical trends in final energy consumption divided by the GDP for Germany between 1991 and 2014 (AG Energiebilanzen, 2015).[8] In the optimistic scenario, a value of 2.1%, which is envisioned by the German government in its concept for the energy transition (Bundesregierung, 2010), is assumed. This improvement declines to 1.9% per year between 2040 and 2050.

Based on this recursive-dynamic setup, the following FDSs are implemented:

- FDS1: Intelligent demand and growth
- FDS2: Demand-driven energy transition with a stagnating economy
- FDS3: Competitive conventional generation
- FDS4: Energy transition without people's support
- FDS5: Cross-sectoral energy transition

[8]Despite serving as the more pessimistic scenario, these exogenous numbers derived from observed energy efficiency improvements are already relatively high.

These distinct, internally consistent scenarios have been generated via the complex scenario-creation process of Gausemeier et al. (1998) and Gausemeier and Plass (2014). Initially, a very large number of possible combinations of attributes (parameters and their values) are taken into consideration. Then, only internally consistent combinations that are free of contradictions are considered further. Finally, diverse clusters of similar combinations are identified, which results in the five FDSs evaluated here. For details, see Blank et al. (2016) and Schwarz et al. (2017).

A set of seven scenario-variant parameters define each FDS in the forward calibration process of our model (see table 1). Together with the five scenario-invariant parameters, these seven parameters represent a subset of all parameters considered in the scenario-creation process. The remaining parameters belong to the disciplines of electrical engineering, behavioral science (psychology), business administration or computer science and thus are not applicable to an economic general equilibrium model (for example, the population's acceptance of stringent climate and energy policy).

Future development scenario FDS1 represents a situation with high economic growth, no structural change towards service sectors in Germany, historical AEEI rates, constant prices of primary energy carriers and an unaltered electricity mix in NWG. This scenario represents a failed transition towards an electricity sector based on renewable technologies in NWG.

Future development scenarios FDS2 and FDS3 share similar assumptions. Worldwide, economic growth is relatively low, and there is no structural change in Germany. Autonomous energy efficiency improvements remain at historical rates, and primary energy carrier prices are constant. The main difference between these scenarios is the electricity mix in NWG. Under FDS2, electricity is generated solely by renewable technologies in 2050, while a small share of fossil fuel-fired power plants remains on the grid under FDS3. The electricity mix of FDS3 has been computed in simulations of an electrical engineering model by Rendel (2015), while the other scenarios share the same electricity mix until 2030. For the later years, the electricity mix under the remaining FDSs is based on the scenario definition developed by the NEDS consortium.

Table 2 summarizes the key assumptions of the five FDSs. In terms of the relevant assumptions for the forward calibration of the economic model, FDS4 and FDS5 are identical. They combine high economic growth and structural change towards service sectors in Germany with optimistic assumptions about AEEIs. In line with Hotelling's theory of the depletion of finite resources, prices for primary energy carriers increase between 2011 and 2050. By 2050, NWG's electricity is quasi-entirely generated by renewables.

Table 2
Parameters of the future development scenarios (FDSs)

		FDS1 Intelligent demand and growth	**FDS2** Demand-driven energy transition with a stagnating economy	**FDS3** Competitive conventional generation	**FDS4** Energy transition without people's support	**FDS5** Cross-sectoral energy transition
1	g_r^{GDP}	High economic growth	Low economic growth	Low economic growth	High economic growth	High economic growth
2	β_r^{AGRI}	No structural change in Germany	No structural change in Germany	No structural change in Germany	Structural change in Germany	Structural change in Germany
3	β_r^{SRV}	No structural change in Germany	No structural change in Germany	No structural change in Germany	Structural change in Germany	Structural change in Germany
4	$g_{i,r}^{AEEI}$	Historical AEEI rates	Historical AEEI rates	Historical AEEI rates	Optimistic AEEI rates	Optimistic AEEI rates
5	$P_{i,r}^{PEC}$	Constant primary energy carrier prices	Constant primary energy carrier prices	Constant primary energy carrier prices	Rising primary energy carrier prices	Rising primary energy carrier prices
6	β_g^{TEC}	Status quo mix (excl. nuclear)	100% Renewables	–80% GHG	100 % Renewables	100% Renewables
7	$\bar{K}_r$	High growth	Low growth	Low growth	High growth	High growth

g_r^{GDP} = growth rate of GDP; β_r^{AGRI} = change in the share of agriculture in value added; β_r^{SRV} = change in the share of services in value added; $P_{i,r}^{PEC}$ = prices of primary energy carriers; $g_{i,r}^{AEEI}$ = autonomous energy efficiency improvements; β_g^{TEC} = share of technology g in power generation (NWG only); $\bar{K}_r$ = capital stock.

3.3 Policy evaluation scenarios

The policy evaluation scenarios (PESs) represent policy strategies envisaged by the governments of NWG. Different from the FDS parameters, the PES parameters can be influenced by the regional governments. The interdisciplinary NEDS consortium has identified three PESs by distinguishing seven fields where the federal states' governments can influence climate and energy policy. Most of these fields reflect highly specific policies that cannot be represented in an economic general equilibrium model, such as standards for smart appliances. Hence, the economic model implementation concentrates on the differences between the three PESs in terms of the technologies used for NWG's power generation and the related costs. These technologies are reflected by the electricity mix in general and by the shares of offshore and onshore wind power in total wind power generation as well as the shares of free-field and rooftop photovoltaics (PVs) in total solar power generation in particular.

- PES1: Local power generation with flexible management; focus on onshore wind power and rooftop PVs
- PES2: Large-scale storage and power generation; focus on offshore wind power and free-field PVs
- PES3: Baseline

The policy evaluation scenarios are implemented via two channels. First, the shares of generation technologies in Northwest Germany's electricity mix slightly differ from each other under each PES. These shares (β_g^{TEC}, see table 1) are computed by the INES electricity dispatch model and implemented as constraints in the forward calibration process. Second, the costs of generating electricity from photovoltaics and wind differ across the PESs depending on the shares of onshore and offshore wind as well as rooftop and free-field PVs in the generation. The model does not explicitly differentiate between types of PVs and wind power. Therefore, an efficiency factor is introduced in the production function of the electricity sector that reflects the fact that onshore wind-derived electricity is generated at lower levelized costs of electricity (LCoEs) than is offshore wind-derived electricity as well as that free-field PVs exhibit lower LCoEs than do rooftop PVs.

The electricity mix of NWG has been computed with the INES model by Rendel (2015) for each PES. Differences between the PESs in the INES model are driven by the available capacity for electricity storage. Under PES1, the storage capacity corresponds to 90% of the values assumed in Faulstich et al. (2016). Under PES2, this fraction is reduced to 60%. Under PES3, the storage capacity equals 30% of Faulstich et al. (2016)'s value.

The investment and maintenance costs of offshore wind turbines are higher than those of onshore turbines. Offshore wind turbines, however, exhibit higher utilization rates, reducing the differences in the LCoE. The study by Faulstich et al. (2016) provides LCoE data for 2030 to 2050. The LCoEs in 2020 are taken from US EIA (2018). Based on these data, a cost factor is quantified for wind power generation that reflects the cost differentials. This factor is held constant under PES3, reduced under PES1 compared to that used in the same period for PES3 (1.46% in 2020, 0.24% in 2030, 0.36% in 2040 and 0.47% in 2050) and increased under PES2 compared to that under PES3 (by the same magnitudes as it is reduced for PES2). The shares of offshore and onshore wind in 2050 are taken from the definition document of the PES and interpolated for the intermediate years (91.29%/8.71% onshore/offshore in 2020, 65.14%/34.86% in 2050).

An analogous approach is employed for PVs. Free-field PV systems exhibit lower costs of solar modules due to economies of scale. Furthermore, free-field PVs can be set up such that the electricity output is maximized, whereas rooftop PVs are constrained by the shape and the angle of the roof upon which they are installed. Therefore, free-field PVs exhibit lower LCoEs than do rooftop PVs. To quantify the cost factor for solar power, we use LCoEs from Prognos (2013, p. 15 and 18), which provides data for northern Germany. The calculations by Prognos (2013) yielded values of 13 ct per kWh for rooftop PVs and 9.2 ct per kWh for free-field PVs. The study by Fraunhofer ISE (2013) yielded similar estimates. While the solar power cost factor is held constant under PES3, it is raised under PES1 compared to that in the same year under PES3 (1.73% in 2020, 3.66% in 2030, 5.82% in 2040 and 8.25% in 2050) and reduced under PES2 compared to under PES3 (by the same magnitudes as it is raised in PES2). It is implicitly assumed that the (shadow) price of land remains constant, which might not be the case if free-field PVs become a major land user in NWG. The shares of free-field and rooftop PVs in 2050 are taken from the same source and interpolated for the intermediate years (11.81%/88.19% free-field/rooftop in 2020, 47.22%/52.78% in 2050).

Together, the PESs' parameters exert countervailing effects on the costs of power generation. The net effect will be determined in the simulations.

4 Results

4.1 Overview

The following subsections present the main results of the forward calibration process and the policy simulations for the five key model regions: Northwest Germany (NWG), the rest of Germany (ROG), France (FRA), the United States (USA) and China (CHN).

First, future development scenarios FDS3 and FDS4/5 are presented in subsections 4.2.1 and 4.2.2 for the baseline policy evaluation scenario (PES3). The results of FDS1, with the failed energy transition, and FDS2 are detailed in appendix C and summarized in subsection 4.2.3. With respect to the parameters of the model, FDS2 differs from FDS3 only in the electricity mix of NWG. FDS4 and FDS5 share macroeconomic assumptions; therefore, the economic model analysis yields identical results.[9]

Second, the outcomes of the policy evaluation scenarios PES1 and PES2 compared to that of PES3 for the future development scenarios FDS3 and FDS4/5 are presented and discussed in subsections 4.3.1 and 4.3.2. Subsection 4.3.3 summarizes the outcomes of the PESs for the remaining FDSs; the corresponding tables can be found in appendix D. To simplify the exposition, appendix E translates the results of the policy evaluation scenarios PES1 and PES2 relative to those of the baseline (PES3) for all FDSs into a qualitative form, in which the −/0/+ signs indicate the direction of variable changes.

4.2 Future development scenarios

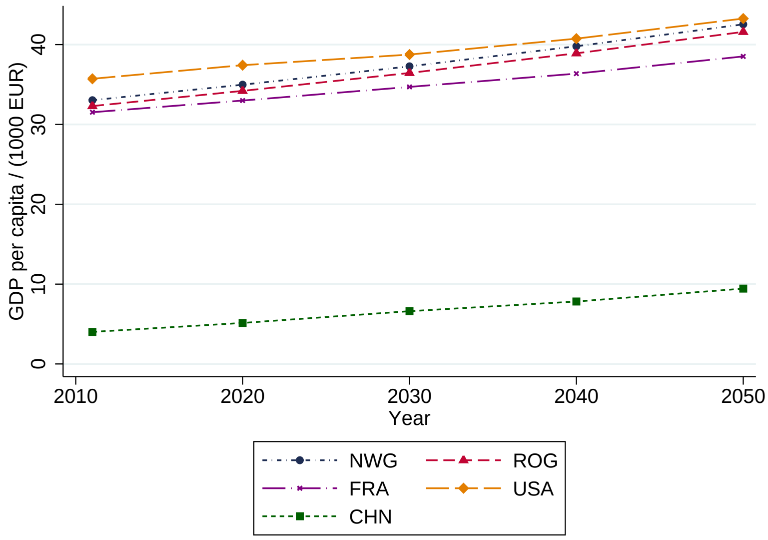
4.2.1 FDS3

Figure 2 shows the evolution of GDP per capita in 1,000 EUR under FDS3 between 2011 and 2050 for the five regions. Note that these outcomes directly follow from the scenario assumptions about GDP and population growth.

In the German regions, GDP per capita increases from approximately 32,000 EUR to 42,000 EUR. Despite having higher absolute growth rates than Germany, the USA's GDP per capita increases to only approximately 43,500 EUR due to a substantially higher population growth rate. FRA also exhibits a higher population increase than Germany, which leads to a smaller increase in GDP per capita than in the German regions. CHN's GDP per capita rises substantially (by 135%) but remains low at 9,400 EUR in absolute terms.

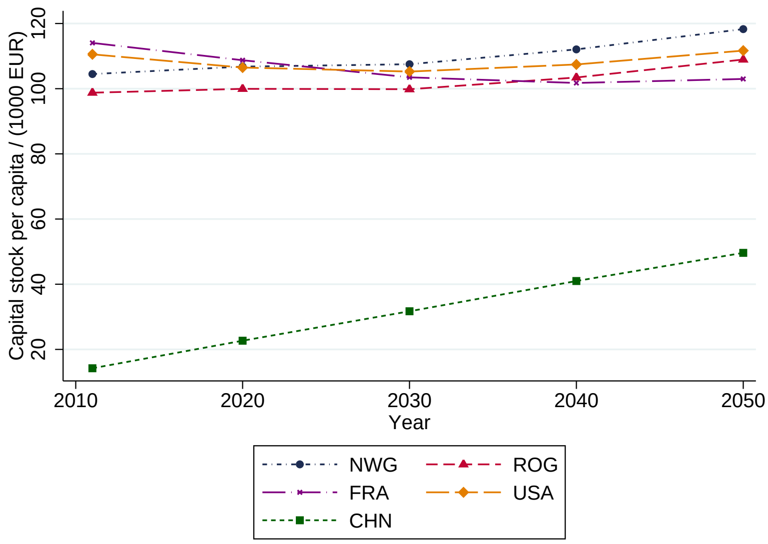
[9]FDS4 and FDS5 differ in corresponding studies of other scientific disciplines in the NEDS consortium.

Figure 2
GDP per capita under FDS3



The evolution of per capita capital stocks depends on the assumptions about GDP growth, population growth and the depreciation rate. Figure 3 illustrates the development of the capital stocks in 1,000 EUR per capita.

Figure 3
Capital stock per capita under FDS3

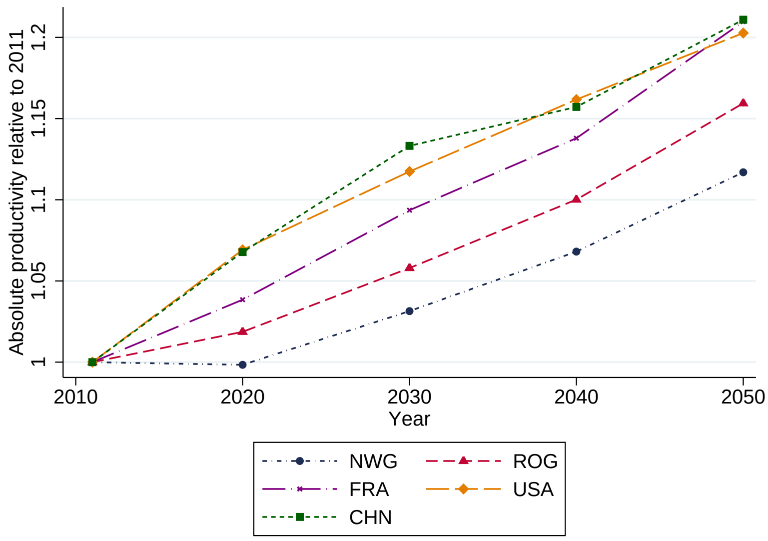


In the two German regions, capital stocks per capita increase between 2011 and 2050 by 13.2% in NWG and 10.3% in the ROG. In the USA, the capital stock per capita remains essentially unchanged over the whole period. The per capita capital stocks in NWG exceed those in the USA from 2030 onwards because the population in the USA is expected to grow until 2050 while that in Germany is expected to decline, according to the UN World Population Prospects. Furthermore, the USA exhibits a substantially smaller savings rate than does Germany. A high savings rate also explains why CHN's capital stock converges quickly to those of Germany and the USA.

The technological progress implied by the forward calibration process is shown in figure 4. This progress constitutes a weighted average of the sectoral productivities ($\widetilde{T}_{i,r}$). The values are normalized to unity in 2011 to simplify the exposition.

Growing by 21.1% between the beginning and the end of the period, CHN exhibits the highest rate of technological progress among the five regions. This rate is, however, much smaller than the targeted 135% growth rate of GDP per capita because in the people's republic, technological progress accompanies substantial savings and capital accumulation, which is the main driver of CHN's economic growth.

Figure 4
Absolute productivity relative to that in 2011 under FDS3



Likewise, the USA achieves a high rate of technological progress, i.e., 20.3%, between 2011 and 2050. In contrast, the USA's capital stock per capita remains virtually constant. Therefore, technological progress rather than capital accumulation is the main driver of the USA's economic growth. NWG, on the other hand, exhibits comparatively low productivity growth under FDS3. NWG is the smallest European region in the model and highly intertwined with the ROG. Therefore, NWG benefits from endogenous productivity increases in the ROG as well as other European regions via international trade and can thus achieve the moderate growth rates assumed under FDS3 without substantial technological progress of its own.

Figure 5
CO_2 emissions relative to those in 2011 under FDS3

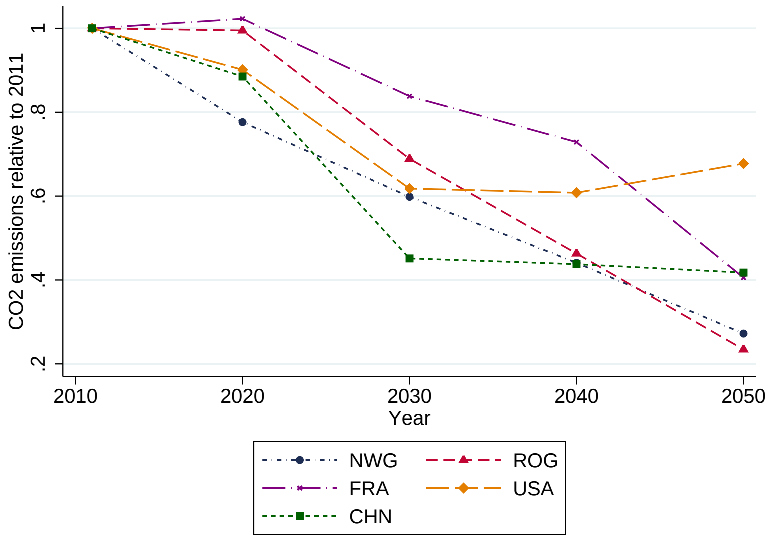


Figure 5 displays the evolution of CO_2 emissions in the five regions. The emissions are normalized to unity in 2011 to simplify the exposition.

In the European regions, CO_2 emissions decline substantially to 27.2% (NWG), 23.4% (ROG), and 40.6% (FRA) of their 2011 values by 2050. These reductions reflect the EU's emission goal, which is implemented via carbon pricing in the ETS sectors and the implicit carbon tax in the remaining sectors. Until 2040, NWG reduces emissions to a greater extent than does the ROG, indicating lower marginal abatement costs in NWG than in the ROG until 2040.

CHN's CO_2 emissions fall by approximately 55% between 2011 and 2030 and remain fairly stable thereafter. The USA's CO_2 emissions fall by 40% between 2011 and 2040 but rise slightly afterwards. In 2050, the emissions in the USA equal 67.8% of their 2011 level. An important explanation for the comparatively low emissions reductions is the absence of carbon pricing in nonindustry sectors and the consumption domain of these regions. These results suggest that CO_2 pricing should be part of a comprehensive climate policy regime in the long run.

Figure 6 depicts the shares of renewable energy technologies in the electricity mix of NWG, the ROG, and FRA in per cent. The renewables share of NWG rises continuously over the period under consideration and converges to 93.0% by 2050. The renewables share of the ROG rises with an increasing slope to 87.8% by 2050. The large renewables share in the ROG is endogenously incentivized by the EU ETS CO_2 price, whereas it is part of the exogenous scenario assumptions in NWG. In FRA, the renewables share remains low (between 12% and 14%) because nuclear power is FRA's major energy source.

Figure 6
Renewables share under FDS3

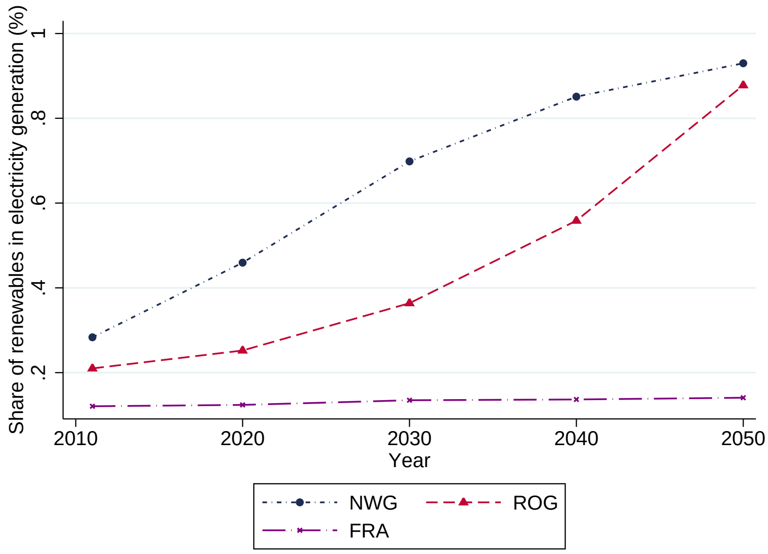


Table 3 displays a number of additional results for the five regions: the share of imported primary energy carriers in electricity generation, the share of final consumption spent on electricity, the wage-to-capital income ratio, the CO_2 price in the EU ETS and the welfare effect of the EU climate policy.

The share of imported primary energy carriers in electricity generation is displayed as an indicator of import dependency and energy security. This share is computed by multiplying the import share of each fossil primary energy carrier (coal, gas, or oil) by its share in electricity generation. While the economic relevance of import dependency is highly disputed, it constitutes an important indicator for political debates regarding the dependence on (politically unstable) energy suppliers. The import share declines in NWG, the ROG, and FRA. While Europe remains highly dependent on imports of coal, natural gas, and crude oil, the increasing share of renewable electricity generation reduces the need to import primary energy carriers for electricity generation.

The share of electricity in final consumption expenditures can be interpreted as a proxy for energy poverty. This share is calculated by dividing the consumption expenditures for electricity by the total consumption expenditures in each year. In NWG, the share declines from 1.07% in 2011 to 0.98% in 2050. Similar developments are found for the other European regions, indicating that the EU's climate policy does not turn electricity into a major budget item for most households. Note, however, that between-household heterogeneity is not considered and that the share of electricity in final consumption expenditures depends on the evolution of the costs of electricity supply, which are hard to predict for an energy system that (almost) exclusively relies on renewables.

Table 3
Results for future development scenario FDS3

	r	2020	2030	2040	2050
Import share of primary energy carriers (%)	*NWG*	12.20	12.96	9.17	3.87
	ROG	31.78	25.24	16.99	5.58
	FRA	9.37	7.55	4.38	1.07
Share of electricity in expenditures (%)	*NWG*	1.12	1.05	0.97	0.98
	ROG	1.06	1.05	0.99	1.00
	FRA	0.97	0.97	0.91	0.93
	USA	1.05	1.06	0.96	0.87
	CHN	1.25	1.23	1.14	1.11
Change in wage-to-capital income ratio (%)	*NWG*	-1.77	-2.06	-2.12	-0.87
	ROG	-1.49	-1.64	-1.73	-1.55
	FRA	-0.12	-0.51	-0.79	-0.78
	USA	0.05	2.72	3.34	3.42
	CHN	1.28	3.21	4.39	5.89
Change in EU ETS price (%)		-35.08	138.60	349.78	1335.57
(EUR/t)		8.79	32.29	60.87	194.27
Welfare change due to European climate policy (%)	*NWG*	-0.03	0.00	-0.11	-1.44
	ROG	-0.06	-0.24	-0.59	-1.68
	FRA	0.01	-1.90	-2.75	-5.31
	USA	0.00	-0.02	-0.03	0.05
	CHN	0.02	-0.19	-0.21	-0.28

The import share of primary energy carriers electricity generation and the share of electricity in consumption expenditures is expressed in per cent. The wage-to-capital income ratio and the EU ETS price are expressed in changes compared to 2011. The EU ETS price is additionally shown in EUR per ton. The welfare effect of the European climate policy is expressed as a percentage change compared to a baseline without European climate policy for year t. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.

The wage-to-capital income ratio serves as a proxy for the distributional effects of the scenarios. Low-income households depend mostly on labor income, while high-income households receive the majority of capital rents. An increase in the wage-to-capital income ratio thus indicates that low-income households gain relatively more than high-income households. The indicator, however, should be treated with caution because heterogeneity within the groups of workers and capital owners is not considered (for a distributional analysis, see Böhringer et al., 2017).

Table 3 displays the change in the wage-to-capital income ratio compared to that in 2011 in per cent. In NWG, the wage-to-capital income ratio decreases slightly between 2011 and 2050. Workers benefit less from the economic developments, while capital owners benefit more. In the ROG and FRA, we observe similar developments. In CHN and the USA, the wage-to-capital income ratio increases in all years, indicating distributional effects in favor of workers.

In table 3, the CO_2 price in the EU ETS (P^{ETS}) is reported as a percentage change compared to the price in 2011 and in EUR per ton. This price rises from a low level of 8.8 EUR per ton in 2020 to 194.3 EUR in 2050. Until 2040, the numbers are lower than those in IEA (2015). Moderate economic growth and the AEEIs allow climate policy to be stringent without requiring extreme CO_2 prices. This effect is particularly pronounced in 2020, when the CO_2 price drops below the 2011 level.

The implicit carbon tax imposed on non-ETS sectors and consumers is introduced in 2030 because the associated emission restriction is previously nonbinding. From 2030 onwards, the reflected marginal abatement costs become substantially higher than the CO_2 price in the EU ETS. In 2050, this cost is approximately three times as large (582.2 EUR per ton). The large difference between these prices indicates that a comprehensive climate policy approach with an equalized price for all emissions in all regions and sectors would create substantial efficiency gains.

Welfare effects are shown in the last five lines of table 3. These effects reflect the change in real consumption due to the implementation of the EU ETS and the implicit carbon tax in non-ETS sectors compared to a baseline without EU climate policy within year t. In 2050, for instance, NWG's welfare declines by 1.44% due to Europe's climate policy compared to a case in which Europe does not implement such a climate policy.

In 2020, welfare effects are small because the EU ETS price is below 10 EUR per ton and the implicit carbon tax is nonbinding. The effects rise substantially by the end of the scrutinized time horizon. NWG and the ROG suffer welfare losses of approximately 1.5% in 2050, while FRA's welfare declines by 5.3%. Whereas the moderate greenhouse gas reduction goals in 2020 can be achieved by reaping low-hanging fruits, an emission reduction of 80% requires fundamental changes in the way goods are produced and consumed and power is generated. Note, however, that welfare gains from mitigated climate change are not considered in these results.

4.2.2 FDS4/5

This subsection displays the results of FDS4/5. These scenarios assume higher GDP growth rates than does FDS3. Furthermore, structural change in Germany and higher AEEIs in all model regions are assumed.

Figure 7 displays GDP per capita in 1,000 EUR between 2011 and 2050 for the five regions. GDP per capita rises to approximately 55,000 EUR in 2050 in the German regions and to 65,500 EUR in the USA. CHN's per capita GDP is approximately five times as large in 2050 as in 2011 (21,700 EUR).

Figure 7
GDP per capita under FDS4/5

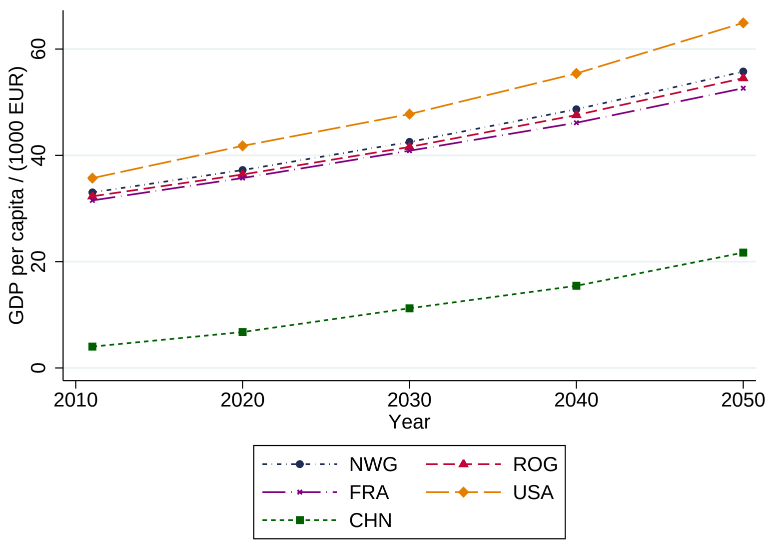
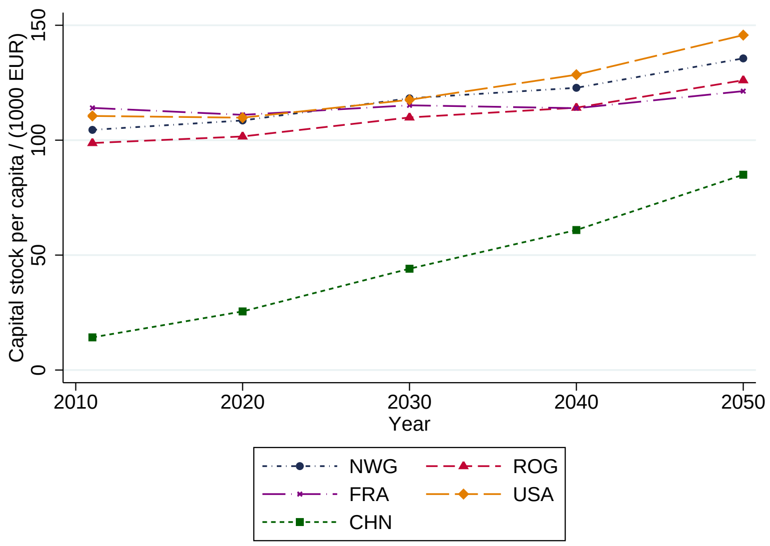


Figure 8
Capital stock per capita under FDS4/5



Capital stocks in 1,000 EUR per capita are depicted in Figure 8. These capital stocks increase in all five regions between 2011 and 2050. In the *USA*, for instance, they rise by 31.8% over the period. Recall that the gross investment grows proportionally to GDP due to the constant savings rate (Solow model). Thus, capital stocks increase more under FDS5 than under FDS3.

Figure 9 displays the absolute productivity by region, normalized to one in 2011. Rising by 48.0% until 2050, *CHN*'s productivity increase is again the highest among the five regions. *NWG* exhibits substantially higher productivity growth under FDS4/5 than under FDS3 (+25.8% compared to +11.7%). While endogenous productivity improvements via technological progress are sufficient in other regions to reach the low growth rates assumed under FDS3, *NWG* must enhance its own absolute productivity substantially to achieve the higher growth rates observed under FDS4/5, because it benefits less from technological progress abroad.

Figure 9
Absolute productivity relative to that in 2011 under FDS4/5

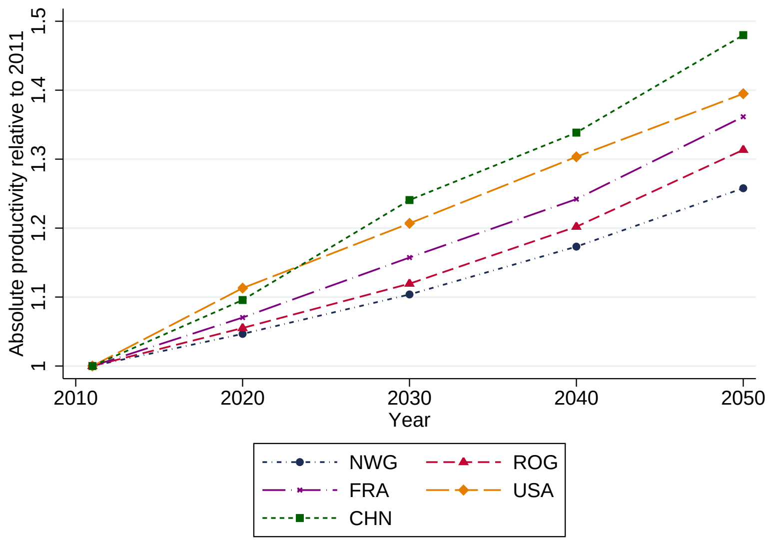


Figure 10 shows CO_2 emissions relative to 2011 levels by region. In Germany, the evolution of emissions is similar to that under FDS3 (figure 5). Emissions fall by 72.3% in *NWG* and by 78.4% in the *ROG*. *CHN*'s emissions decline to 47.9% of their 2011 level in 2050. This decline is approximately seven percentage points lower than that under FDS3. The *USA*'s CO_2 emissions fall by approximately one quarter until 2030 and rise again thereafter. While stringent climate policy keeps Europe's emissions at the same levels as those observed under FDS3, higher economic growth rates lead to more emissions under FDS4/5 than under FDS3 outside of the EU. These results emphasize the importance of global climate policy coverage.

Figure 10
CO_2 emissions relative to those in 2011 under FDS4/5

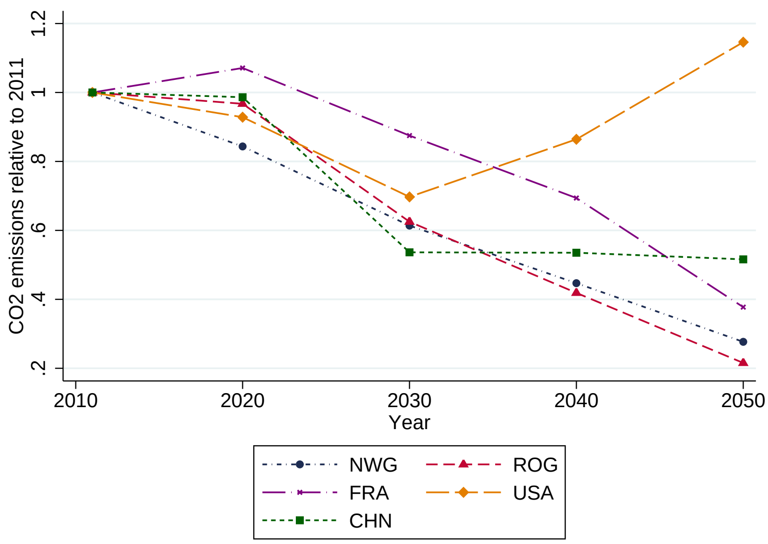


Figure 11
Renewables share under FDS4/5

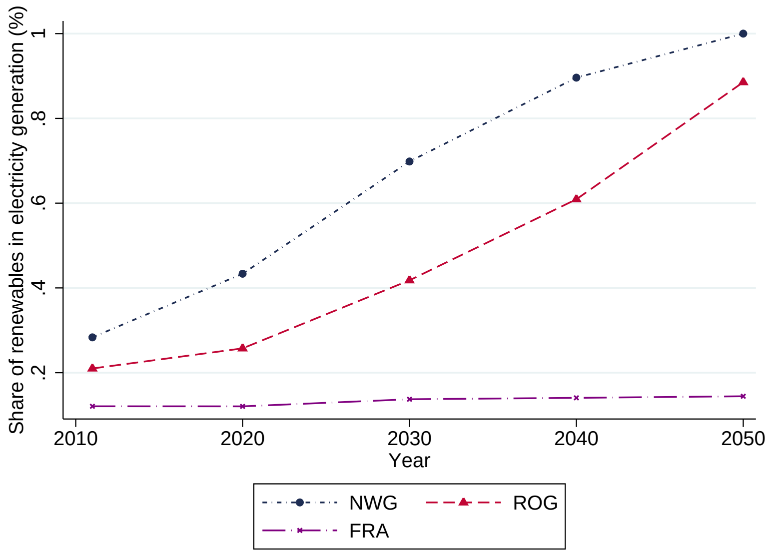


Figure 11 displays the share of renewables in NWG, the ROG, and FRA in per cent. Following the assumptions of FDS4/5, NWG reaches a renewables share of quasi-100% by the end of the time horizon. The ROG's share reaches 88.5%, while FRA's renewables share remains low at 14.4% in 2050.

Table 4 presents additional results for FDS4/5. These results correspond to the indicators shown in table 3. As under FDS3, the share of imported primary energy carriers in electricity generation falls substantially between 2011 and 2050 under FDS4/5. Due to an electricity mix based entirely on renewables, NWG does not import any primary energy carriers for electricity generation in 2050.

The share of electricity in the final consumption in NWG declines to 0.84% in 2050.

This share is thus slightly lower than that observed under FDS3, indicating that neither FDS3 nor FDS4/5 gives rise to a fuel poverty problem.

Table 4
Results for future development scenario FDS4/5

	r	2020	2030	2040	2050
Import share of primary energy carriers (%)	NWG	13.36	12.77	3.51	0.00
	ROG	33.13	23.78	14.15	4.29
	FRA	9.53	6.58	3.73	0.87
Share of electricity in expenditures (%)	NWG	1.03	0.97	0.89	0.84
	ROG	1.02	1.00	0.93	0.91
	FRA	0.93	0.93	0.86	0.85
	USA	1.05	1.00	0.88	0.78
	CHN	1.27	1.28	1.18	1.10
Change in wage-to-capital income ratio (%)	NWG	-1.54	-2.70	-3.73	-4.32
	ROG	-0.50	-1.25	-0.18	1.72
	FRA	-0.43	-0.85	-1.31	-1.36
	USA	1.83	5.19	6.40	7.02
	CHN	1.99	4.89	6.66	8.55
Change in EU ETS price (%)		-24.39	175.88	414.43	1653.39
(EUR/t)		10.23	37.33	69.61	237.28
Welfare change due to European climate policy (%)	NWG	0.01	-0.01	0.07	-0.48
	ROG	-0.03	-0.16	-0.20	-0.67
	FRA	-0.28	-2.14	-2.54	-4.36
	USA	0.00	0.01	0.06	0.14
	CHN	0.01	-0.21	-0.22	-0.26

The import share of primary energy carriers electricity generation and the share of electricity in consumption expenditures is expressed in per cent. The wage-to-capital income ratio and the EU ETS price are expressed in changes compared to 2011. The EU ETS price is additionally shown in EUR per ton. The welfare effect of the European climate policy is expressed as a percentage change compared to a baseline without European climate policy for year t. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.

The wage-to-capital income ratio declines continuously in NWG between 2011 and 2050. By the end of the time horizon, the ratio is 4.3% lower than that in 2011, compared to 0.9% lower under FDS3. Capital owners in NWG benefit more from the higher growth rates than do laborers. The ROG, however, exhibits an increase in the wage-to-capital ratio in 2050. In the USA and CHN, the wage-to-capital income ratio rises compared to that in 2011 in all years.

The CO_2 prices under FDS4/5 are higher than those under FDS3 in all years. Due to the stronger economic growth under FDS4/5, higher CO_2 prices are necessary to enforce the equivalent emission reduction goals. The combination of greater AEEIs, a structural change towards services in Germany, and an electricity mix based on renewables in NWG can partially compensate for the higher growth rates. While exceeding the level of FDS3, the CO_2 price in 2020 is still below that of 2011, which indicates that the reduction goal for 2020 is not very ambitious, at least under the assumed AEEI rates. The implicit carbon tax is, again, nonbinding until 2030. From 2030 onwards, the price is approximately three times as high as the EU ETS price.

Surprisingly, the welfare effects of the EU climate policy are lower under FDS4/5 than under FDS3, despite the higher CO_2 prices. Three factors can explain this surprising result. First, NWG's *exogenously* given electricity mix consists exclusively of renewables under FDS4/5. This lack of diversity eases the introduction of climate policy. Second, higher AEEI rates reduce the importance of energy for the economy. Third, larger absolute productivity improvements make the European economies more efficient.

4.2.3 Remaining FDSs

FDS1 represents a situation in which the transition towards power generation based on renewables in NWG fails. This scenario exhibits high economic growth rates, no structural change towards services in Germany and historical AEEI rates. The electricity mix in NWG remains unchanged from 2030 onward. The forward calibration process finds that high absolute productivity improvements are necessary to achieve the growth rates of FDS1, in particular between 2040 and 2050. In NWG, absolute productivity rises by 55.7% between 2011 and 2050, which is almost as large as the increase observed in CHN (+57.9%). The productivity growth helps Europe meet its emissions target. The CO_2 price of 193.80 EUR per ton in the EU ETS in 2050 is below that under FDS4/5 even though the latter FDS exhibits structural change and higher AEEI rates. Unlike under the other FDSs, the restriction of non-ETS emissions is already binding by 2030. In contrast, in NWG, the failed energy transition has substantial effects. While NWG's emissions reduction by 2050 declines to 60% compared with more than 70% under other scenarios, the welfare loss reaches 15.8%.

FDS2 is based on assumptions similar to those of FDS3. The two scenarios differ in their assumptions about the electricity generation in NWG. While some electricity is generated from fossil fuels until 2050 under FDS3, the electricity mix under FDS2 is based entirely on renewables by the end of the period. Despite similar assumptions, the forward calibration process yields a different productivity growth path for FDS2 than for FDS3. Productivity growth in NWG is higher under FDS2 than under FDS3 but lower in other regions including the ROG and CHN. This difference leads to slightly higher CO_2 prices (200.4 EUR in 2050) under FDS2 than under FDS3.

4.3 Policy evaluation scenarios

4.3.1 PESs under FDS3

Table 5 displays the results of PES1 and PES2 as changes relative to PES3, which serves as the baseline, in per cent within each year (t). Recall that the shares of onshore wind generation and rooftop PVs under PES1 are increased compared to those under PES3, while the shares of offshore wind and free-field PVs are higher under PES2.

The effects of the PESs on GDP per capita are small. The changes do not exceed one per mill in any region. The strongest effects are observed for NWG in 2050 (–0.07% in PES1 and +0.07% in PES2). The negative GDP effects under PES1 indicate that the higher costs of installing more rooftop PVs dominate the lower costs of installing more onshore wind power.

The PESs' effects on the absolute productivity in NWG are larger than those on GDP. Under PES1 and PES2, the absolute productivity in 2020 is over one per cent higher than that under PES3. From 2040 onward, however, the productivities fall below those observed under PES3. The absolute productivities in regions other than NWG are not notably affected.

The German nuclear phase out is visible in the results for 2030. For example, because FDS3 relies on fossil energies, NWG replaces nuclear power with fossil energy-based power, which raises emissions. This transitional effect is created by the input data from the INES energy dispatch model and disappears in 2040.

The renewables share and therefore the import share of primary energy carriers for electricity generation are affected substantially by the PESs. The electricity mix is provided by the INES model (Rendel, 2015), which operationalizes the policy evaluation scenarios by the electricity storage capacity in NWG. Under PES1, the capacity is large, whereas under PES3, it is small. In the absence of large electricity storages, gas-fired power plants have to balance supply and demand for electricity. Therefore, PES1 and PES2 achieve higher renewables shares than does PES3, and the imports of primary energy carriers for electricity generation decline.

Table 5
Results of the policy evaluation scenarios for FDS3

		PES1				PES2			
	r	2020	2030	2040	2050	2020	2030	2040	2050
GDP per capita	*NWG*	0.00	-0.03	-0.05	-0.07	0.00	0.02	0.05	0.07
	ROG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	FRA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	USA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CHN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Regional absolute productivity	*NWG*	1.06	0.25	-0.77	-0.42	1.18	0.15	-1.15	-0.58
	ROG	0.03	0.03	0.01	-0.01	0.03	0.03	0.01	-0.02
	FRA	0.01	0.00	-0.01	0.00	0.01	0.00	-0.01	0.00
	USA	0.00	0.01	0.06	0.00	0.00	0.01	0.06	0.01
	CHN	0.01	0.02	-0.05	-0.09	0.01	0.02	-0.05	-0.09
CO_2 emissions	*NWG*	-1.21	0.72	-0.86	-1.03	-1.35	0.68	-0.95	-0.85
	ROG	0.04	-0.03	0.04	0.04	0.05	-0.03	0.04	0.03
	FRA	0.02	-0.01	0.01	0.03	0.02	0.00	0.01	0.03
	USA	-0.01	-0.01	-0.03	-0.04	-0.01	-0.01	-0.03	-0.04
	CHN	0.00	0.00	0.01	0.02	0.00	0.00	0.01	0.02
Renewables share	*NWG*	8.66	3.35	0.97	1.42	7.74	3.80	1.31	1.52
	ROG	-0.06	0.05	-0.05	-0.04	-0.06	0.04	-0.07	-0.04
	FRA	-0.01	0.01	0.00	-0.01	0.00	0.00	-0.01	-0.01
Import share of primary energy carriers	*NWG*	-8.48	-21.02	-4.37	-19.31	-7.47	-22.09	-5.87	-20.43
	ROG	0.00	-0.23	-0.03	0.04	0.00	-0.21	-0.01	0.10
	FRA	0.08	-0.07	0.09	0.27	0.09	-0.05	0.11	0.28
Share of electricity in consumption expenditures	*NWG*	0.19	0.45	0.55	0.58	0.24	0.11	-0.09	-0.22
	ROG	-0.01	0.01	0.00	0.00	0.00	0.01	-0.01	-0.01
	FRA	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	USA	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00
	CHN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01
Wage-to-capital income ratio	*NWG*	0.05	0.05	0.07	0.09	0.03	0.02	0.00	0.00
	ROG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	FRA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	USA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CHN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2 price in the EU ETS		-0.32	0.15	-0.05	-0.22	-0.31	0.09	-0.12	-0.26

All results for policy evaluation scenarios PES1 and PES2 are expressed in percentage changes compared to PES3 in t in per cent. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.

NWG's CO_2 emissions are mostly lower under PES1 and PES2 than under PES3, which can be explained by higher renewables shares. Neither the CO_2 price in the EU ETS nor the share of electricity in total consumption expenditures or the wage-to-capital income ratio significantly differs among the PESs.

4.3.2 PESs under FDS4/5

The results of the policy evaluation scenarios for future development scenario FDS4/5 are displayed in table 6. The effects of the PESs on GDP are small under FDS4/5. The GDP changes only exceed one per mill in *NWG* in 2050 (–0.15% in PES1 and +0.16% in PES2). The changes in *NWG*'s absolute productivity are of the same order of magnitude as those under FDS3. The largest effects are found for 2050, when the absolute productivities under PES1 and PES2 exceed those under PES3 by 2.75% and 1.83%, respectively.

Varying by more than one per cent in several countries and years, the absolute productivities outside of *NWG* are affected more substantially under FDS4/5 than under FDS3. This discrepancy indicates that the modest differences between the PESs affect the technology growth paths.

In contrast to the results observed for FDS3, the German nuclear phase out induces an emissions reduction via a significant expansion of renewables in *NWG* in 2030. The *ROG*, however, expands fossil energies such that emissions rise in the transitional year 2030.

The renewables shares are higher under PES1 and PES2 than under PES3. Therefore, the shares of imported primary energy carriers decline in both PESs. Rarely exceeding one per cent, the PESs' effects on the share of electricity in final consumption and on the wage-to-capital income ratio are limited. Overall, 2030 appears to be affected most significantly by the PESs.

NWG's CO_2 emissions are slightly lower under PES1 than under PES2. As for FDS3, this difference can be attributed to the lower capacity for electricity storage under PES3, which serves as the baseline PES. The years 2040 and 2050 are exceptions: their CO_2 emissions under PES2 are slightly higher than those under the baseline PES3.

Table 6
Results of the policy evaluation scenarios for FDS4/5

		PES1				PES2			
	r	2020	2030	2040	2050	2020	2030	2040	2050
GDP per capita	*NWG*	0.00	-0.04	-0.09	-0.15	0.00	0.04	0.09	0.16
	ROG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	FRA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	USA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CHN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Regional absolute productivity	*NWG*	-0.48	-1.65	0.48	2.75	-0.48	-1.42	-0.45	1.83
	ROG	0.00	1.91	0.30	0.27	0.00	1.74	-0.30	-0.27
	FRA	-0.01	0.98	0.18	0.73	-0.01	0.59	-0.18	0.14
	USA	0.00	-2.66	-0.58	2.68	0.00	-2.30	0.55	2.14
	CHN	0.00	1.10	0.33	-0.30	0.00	0.65	-0.32	1.06
CO_2 emissions	*NWG*	-0.90	-3.97	-0.38	0.00	-0.96	-3.25	0.39	0.98
	ROG	0.04	1.89	-0.06	0.08	0.04	1.32	0.06	-0.05
	FRA	0.02	-1.84	-0.17	0.05	0.02	-1.20	0.15	0.08
	USA	0.00	2.15	0.78	-1.38	0.00	1.87	-0.73	-2.16
	CHN	-0.01	-2.16	-0.30	0.50	-0.01	-1.89	0.29	0.78
Renewables share	*NWG*	0.58	3.39	0.04	0.00	-0.81	3.76	-0.05	0.00
	ROG	-0.06	-0.68	0.06	0.03	-0.07	-0.45	-0.06	0.06
	FRA	-0.02	0.20	0.06	0.06	-0.02	0.18	-0.06	0.01
Import share of primary energy carriers	*NWG*	-1.61	-17.36	-0.31	-	-0.30	-18.23	0.35	-
	ROG	0.00	-0.36	-0.12	-0.21	0.01	-0.39	0.11	0.26
	FRA	0.09	0.34	-0.42	-0.73	0.09	0.23	0.41	-0.26
Share of electricity in consumption expenditures	*NWG*	-0.01	1.72	0.59	0.33	-0.01	1.10	-0.55	-0.92
	ROG	-0.01	-0.46	0.03	0.24	-0.01	-0.35	-0.03	0.11
	FRA	-0.01	-0.22	-0.01	0.19	-0.01	-0.21	0.01	0.10
	USA	0.00	-1.14	-0.10	0.34	0.00	-0.96	0.10	0.32
	CHN	0.00	0.16	0.09	0.11	0.00	0.19	-0.09	-0.26
Wage-to-capital income ratio	*NWG*	-0.01	0.55	0.05	-0.06	-0.03	0.36	-0.05	-0.26
	ROG	0.00	-0.49	-0.03	0.04	0.00	-0.38	0.03	0.05
	FRA	0.00	0.04	0.00	0.00	0.00	0.02	0.00	0.00
	USA	0.00	0.17	0.01	0.04	0.00	0.13	-0.01	0.05
	CHN	0.00	0.09	0.01	-0.02	0.00	0.08	-0.01	-0.04
CO_2 price in the EU ETS		-0.44	-7.89	-0.11	1.16	-0.47	-6.51	0.11	1.19

All results for policy evaluation scenarios PES1 and PES2 are expressed in percentage changes compared to PES3 in t in per cent. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.

4.3.3 PESs for the remaining FDSs

Under FDS1 (appendix table D1), the absolute productivities implied by the forward calibration process are sensitive to the PES. In 2050, NWG's absolute productivity is 13.6% lower under PES1 and 15.9% lower under PES2 than under PES3. The CO_2 emissions under both PESs are between 0.5% and 3% lower than that those under PES3. Overall, the outcomes for 2050 are most sensitive to changes in the electricity mix.

The PESs affect FDS2 (table D2) similarly to FDS3 in 2020 and 2030 because we assume that the electricity mix evolves in the same way. From 2040 onwards, NWG's absolute productivity reacts more significantly to the PES under FDS2 than under FDS3. The CO_2 emissions are lower under PES1 than under PES3 but higher under PES2 from 2040 onwards, despite higher renewables shares. The impacts on the share of electricity in final consumption and the wage-to-capital income ratio are small.

The PESs have similar effects on GDP per capita under all FDSs. These effects are slightly weaker under PES1 and slightly higher under PES2. Under some FDSs, in particular FDS1, the evolution of absolute productivities is sensitive to changes in the PES's assumptions. Due to the complex combination of assumptions underlying each FDS, implied productivity developments are not always robust to the changes in the PES.

While the CO_2 emissions in NWG are visibly affected by the PES, the CO_2 price in the EU ETS is generally not visibly affected. This finding confirms that a subnational government can hardly exert a substantial influence on supraregional economic or policy variables. Particularly, the avoided emissions in NWG are compensated for by additional emissions in other European regions (carbon leakage).

5 Conclusion

This article has introduced a numerical forward calibration method to parameterize computable general equilibrium models, especially new quantitative trade (NQT) models, based on elaborated scenario assumptions. Formulated as a non-linear optimization problem, the method transparently and reproducibly determines patterns of technological progress complying with a set of complex assumptions about economic developments.

The future development scenarios, which represent a set of assumptions about economic growth, structural and technological change as well as climate policy, provide the following insights. First, via international trade connections, small open economies, such as that of Northwest Germany, can achieve moderate economic growth by benefiting from endogenous productivity increases induced by technological progress in other parts of the world. To achieve higher growth rates, however, such economies require domestic technological progress.

Second, climate policy can effectively reduce CO_2 emissions in Europe at moderate CO_2 prices in the EU ETS. This outcome does not mean, however, that stringent climate policy is easy to implement at low cost. In the forward calibration process, the EU ETS is accompanied by measures for non-ETS and consumers' emissions, exogenous energy efficiency improvements and exogenous structural change. The moderate CO_2 prices indicate that the interplay of these instruments works well, reflected by small welfare losses. Furthermore, the climate policy-induced welfare losses drastically increase when the reduction target approaches 80% towards 2050. If Northwest Germany's energy transition fails, then its climate policy costs can drastically rise to 16% by 2050.

Third, an additional implicit carbon tax representing any other mitigation measures ensures that emissions reductions in Europe's non-ETS sectors and in the consumption domain are in line with the EU Roadmap 2050. From 2030 onwards, the reflected marginal abatement costs are approximately threefold higher than the CO_2 price in the EU ETS. This result accords with Germany's difficulties in achieving the required CO_2 reductions outside the EU ETS and indicates that a uniform CO_2 price in all sectors would significantly raise welfare.

Fourth, a comparison of the future development scenarios suggests that high autonomous energy efficiency improvements and exogenous structural change towards service industries can compensate for CO_2 emissions created by reasonably higher economic growth.

The policy evaluation scenarios represent differences in the Northwest German electricity mix, particularly the shares of onshore and offshore wind power in total wind power generation as well as the shares of free-field and rooftop PVs in total solar power generation. These policies can be directly influenced by the federal states' governments.

The comparison of these scenarios reveals that regional support for specific wind or solar power technologies affects the renewables share and thereby the import share of primary energy carriers and creates small positive or negative effects on GDP and households' expenditures. Accordingly, regional policies that support specific technologies can create unanticipated (negative) local outcomes.

Some results of the policy evaluation scenarios differ depending on the future development scenario. For example, Northwest Germany's electricity mix affects the evolution of its absolute productivities, which in turn influences outcomes of the forward calibration process, such as regional CO_2 emissions.

The results, however, should be interpreted with care. From a policy perspective, the simulations of the policy evaluation scenarios indicate that subnational regions are unlikely to influence international climate policy substantially. Hence, regional disaggregation is not necessary as long as subnational effects or policies are of no particular interest. If, however, subnational policies are debated, regional disaggregation is recommendable to obtain region-specific results. Based on these results, subnational policy makers may wisely combine the policies imposed at higher regional or jurisdictional levels with local measures to avoid counterproductive local policy interactions.

From a modeling perspective, the number and complexity of the assumptions underlying each future development scenario pose a challenge. While the forward calibration process determines a path of technological progress in line with the assumptions, the sensitivity increases with the number and complexity of the assumptions. Researchers applying the forward calibration process should therefore carefully consider the degree of complexity required.

6 Acknowledgment

We gratefully acknowledge funding for the project "NEDS – Nachhaltige Energieversorgung Niedersachsen" supported by the Lower Saxony Ministry of Science and Culture and the Volkswagen Foundation through the "Niedersächsisches Vorab" grant program (grant ZN3043).

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Supplementary online appendix

A Definition of sectors and regions

Table A1 lists all sectors i in the model and their participation in the EU ETS.

Table A1
Sectors in the model

i	Description	ETS
$AGRI$	Agriculture	No
$COAL$	Coal	No
$CRUD$	Crude oil	No
$NGAS$	Natural gas	No
$PETR$	Refined petroleum	Yes
$FOOD$	Food production	No
$MINE$	Mining	No
$PAPR$	Paper and pulp	Yes
$CHEM$	Chemical products	Yes
$NMMS$	Mineral products nec	Yes
$IRST$	Iron and steel	Yes
$NFMS$	Nonferrous metals	Yes
$MANU$	Manufacturing	No
$ELEC$	Electricity	Yes
$TRNS$	Transport	No
$CONS$	Construction	No
$SERV$	Services	No
$INVS$	Investment	No

The investment sector $INVS$ combines intermediate inputs into a (nontradable) gross investment good. nec = not elsewhere classified.

The regions r considered in the model are displayed in table A2. The column TSE indicates whether technology-specific power generation is considered in r.

Table A2
Regions in the model

r	Description	TSE	r	Description	TSE
NWG	Northwest Germany	Yes	CAN	Canada	No
ROG	Rest of Germany	Yes	KOR	Korea	No
USA	United States	No	FSU	Former Soviet Union	No
CHN	China incl. Hong Kong	No	OCE	Australia and Oceania	No
JPN	Japan	No	MEX	Mexico	No
GBR	United Kingdom	Yes	EUR	Rest of the European Union	No
FRA	France	Yes	ROE	Rest of Europe	No
IND	India	No	ROA	Rest of Asia	No
ITA	Italy	Yes	ROW	Rest of the World	No
BRA	Brazil	No			

Northwest Germany (NWG) encompasses the federal states of Lower Saxony (Niedersachsen), Hamburg and Bremen.

B Structural estimation results

Table B1 displays the sector-specific results of the structural estimation procedure. All sectors are listed with their description and their estimated shape parameter of the Fréchet distribution (θ_i), which constitutes the inverse spread of variety-specific productivities. Furthermore, table B1 displays the elasticity of distance (μ_i) between the sector-specific constant (β_i^0) and the dummy variables explaining the iceberg trade costs: the fixed effects of a common border (β_i^1), the fixed effects of a common language (β_i^2), the fixed effects of two countries sharing a colonial history (β_i^3), the effects of having a regional trade agreement in place (β_i^4), and the effects of sharing a common currency (β_i^5). Standard deviations obtained from 1,000 bootstrap iterations are shown in parentheses.

Table B1
Sectoral estimates of the EK param. θ_i and det. of iceberg costs $\ln \tilde{\delta}_{i,r,s}$

		Dep. var.: normalized trade share $\ln\left(\frac{\pi_{i,r,s}}{\pi_{i,s,s}}\right)$							
Sector i	Description	Inv. spread of product θ_i	distance elasticity μ_i	constant β_i^0	border FE β_i^1	language FE β_i^2	colony FE β_i^3	rtrade FE β_i^4	currency FE β_i^5
AGRI	Agriculture	2.72	0.27	1.52	-0.32	-0.31	-0.02	-0.30	-0.08
		(0.38)	(0.05)	(0.25)	(0.07)	(0.10)	(0.05)	(0.07)	(0.06)
COAL	Coal	10.03	0.14	0.33	-0.09	-0.06	-0.08	-0.03	-0.02
		(0.70)	(0.02)	(0.05)	(0.02)	(0.02)	(0.03)	(0.01)	(0.01)
CRUD	Crude oil	7.86	0.20	0.58	0.01	-0.41	0.04	-0.02	0.25
		(0.61)	(0.03)	(0.07)	(0.02)	(0.03)	(0.03)	(0.02)	(0.03)
NGAS	Natural gas	7.92	0.14	0.66	-0.07	-0.17	-0.06	-0.16	0.01
		(1.87)	(0.03)	(0.23)	(0.05)	(0.06)	(0.04)	(0.08)	(0.03)
PETR	Refined petroleum	9.03	0.11	0.24	-0.06	0.00	-0.05	-0.01	0.00
		(0.87)	(0.01)	(0.07)	(0.04)	(0.03)	(0.03)	(0.01)	(0.01)
FOOD	Food production	3.73	0.18	0.91	-0.15	-0.11	-0.12	-0.08	-0.08
		(0.36)	(0.02)	(0.14)	(0.04)	(0.04)	(0.03)	(0.04)	(0.05)
MINE	Mining	2.20	0.30	1.30	-0.31	-0.62	0.01	0.01	0.13
		(0.43)	(0.05)	(0.37)	(0.14)	(0.14)	(0.07)	(0.07)	(0.10)
PAPR	Paper and Pulp	5.22	0.16	0.62	-0.11	-0.07	-0.04	-0.05	-0.06
		(0.40)	(0.02)	(0.09)	(0.04)	(0.03)	(0.02)	(0.03)	(0.03)
CHEM	Chemicals	4.49	0.16	0.42	-0.07	-0.03	-0.05	-0.03	-0.02
		(0.21)	(0.01)	(0.05)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
NMMS	Mineral products	6.37	0.11	0.50	-0.09	0.01	-0.06	-0.01	-0.05
		(0.30)	(0.01)	(0.05)	(0.03)	(0.02)	(0.02)	(0.02)	(0.03)
IRST	Iron and steel	4.27	0.23	0.46	-0.04	-0.08	-0.03	-0.09	-0.08
		(0.35)	(0.02)	(0.08)	(0.03)	(0.03)	(0.02)	(0.04)	(0.04)
NFMS	Non-ferrous metals	4.52	0.21	0.22	-0.04	-0.01	-0.03	-0.05	-0.04
		(0.36)	(0.02)	(0.09)	(0.03)	(0.04)	(0.03)	(0.04)	(0.03)
MANU	Manufacturing	5.04	0.10	0.51	-0.10	0.01	-0.05	-0.04	-0.03
		(0.21)	(0.01)	(0.05)	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)
ELEC	Electricity	18.41	0.05	0.39	-0.05	-0.01	-0.02	0.02	-0.01
		(0.40)	(0.01)	(0.03)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
TRNS	Transport	6.05	0.04	0.80	-0.04	-0.03	-0.02	-0.01	0.02
		(0.27)	(0.01)	(0.04)	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)
CONS	Construction	14.94	0.01	0.56	0.01	-0.05	0.02	0.01	0.02
		(0.62)	(0.01)	(0.03)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
SERV	Services	6.25	0.05	0.96	-0.04	-0.02	0.00	0.00	-0.06
		(0.22)	(0.01)	(0.03)	(0.01)	(0.02)	(0.01)	(0.01)	(0.02)

Standard deviations obtained from 1000 bootstrap iterations in parentheses.

Region-specific results are shown in table B2, which lists all regions of the model as well as four outcomes of the estimation: the absolute productivity in region r (T_r), which constitutes a weighted average of the sectoral productivities ($T_{i,r}$), normalized by the USA's productivity to facilitate the comparison; the endogenous productivity, which is subject to the productivity-enhancing effect of international trade (Λ_r), also normalized by the USA's value; the weighted average of the shape parameters of the Fréchet distribution (θ_r); and the importer fixed effect on the iceberg trade costs, which represents country-specific barriers against imports.

Table B2
Weighted regional averages of key parameter estimates

Dep. var.: normalized trade share $\ln\left(\frac{\pi_{i,r,s}}{\pi_{i,s,s}}\right)$					
Region r	Description	Absolute productivity T_r	Endogenous productivity Λ_r	Inv. spread of product. θ_r	Importer FE $\tilde{m}_r$
NWG	North-West Germany	1.20	1.47	6.44	0.11
		(0.01)	(0.01)	(0.16)	(0.02)
ROG	Rest of Germany	1.33	1.60	6.36	-0.14
		(0.01)	(0.01)	(0.15)	(0.02)
FRA	France	1.34	1.55	6.60	0.10
		(0.01)	(0.01)	(0.16)	(0.02)
FSU	Former Soviet Union	0.77	0.90	7.39	0.01
		(0.01)	(0.01)	(0.18)	(0.01)
GBR	United Kingdom	1.45	1.69	6.69	-0.15
		(0.01)	(0.01)	(0.17)	(0.01)
ITA	Italy	1.08	1.26	6.55	0.08
		(0.01)	(0.01)	(0.15)	(0.02)
EUR	Rest of EU	1.27	1.49	6.72	-0.27
		(0.01)	(0.01)	(0.15)	(0.02)
ROE	Rest of Europe	1.43	1.64	6.99	0.17
		(0.01)	(0.01)	(0.19)	(0.02)
BRA	Brazil	1.01	1.18	6.19	0.19
		(0.01)	(0.01)	(0.15)	(0.02)
CAN	Canada	1.46	1.70	6.83	0.09
		(0.01)	(0.01)	(0.17)	(0.02)
MEX	Mexico	0.66	0.78	6.56	0.36
		(0.01)	(0.01)	(0.15)	(0.02)
USA	United States	1.77	2.02	6.66	-0.26
		(0.01)	(0.00)	(0.17)	(0.02)
CHN	China incl Hong Kong	0.93	1.10	6.31	-0.21
		(0.01)	(0.01)	(0.13)	(0.02)
IND	India	0.76	0.89	6.68	0.06
		(0.01)	(0.01)	(0.15)	(0.02)
JPN	Japan	1.28	1.46	6.55	0.09
		(0.01)	(0.01)	(0.16)	(0.02)
KOR	Korea	1.01	1.19	6.38	-0.03
		(0.01)	(0.01)	(0.14)	(0.02)
ROA	Rest of Asia	0.73	0.88	6.32	-0.29
		(0.01)	(0.01)	(0.14)	(0.02)
OCE	Australia and Oceania	1.28	1.48	7.03	0.09
		(0.01)	(0.01)	(0.17)	(0.02)
ROW	Rest of the World	0.95	1.14	6.74	-0.29
		(0.01)	(0.01)	(0.16)	(0.02)

Standard deviations obtained from 1000 bootstrap iterations in parentheses.

Both the sector-specific (table B1) and region-specific (table B2) results are very similar to those of Pothen and Hübler (2018) because the same estimation procedure and similar data are used.

C Remaining future development scenarios

C.1 FDS1

These subsections display the results of the remaining future development scenarios, namely, FDS1 and FDS2. The discussion focuses on Northwest Germany (NWG).

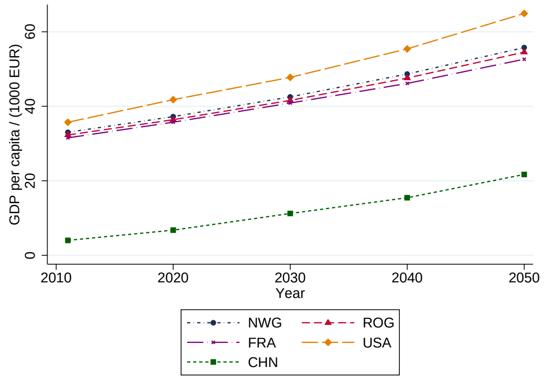
Future development scenario FDS1 represents a situation in which the transition towards renewables-based electricity generation in NWG fails. Figures C1a to C1e display GDP per capita (in 1,000 EUR), the capital stock per capita (in 1,000 EUR), the regional productivity (normalized to 1 in 2011), the CO_2 emissions (normalized to 1 in 2011), and the renewables share (in %) in the same five regions that were presented for FDS3 and FDS4/5.

FDS1 assumes that GDP and thereby capital stocks grow at the same high rates as those under FDS4 and FDS5 between 2011 and 2050 (figure C1a and C1b). Productivity growth under FDS1 resembles that under FDS4/5 until 2040. In 2050, NWG exhibits a substantially higher increase in absolute productivity than it does under FDS4/5 (48.3% compared to 25.8%). In the ROG, the absolute productivity in 2050 also rises more under FDS1 than under FDS4/5. The opposite is the case for most other regions.

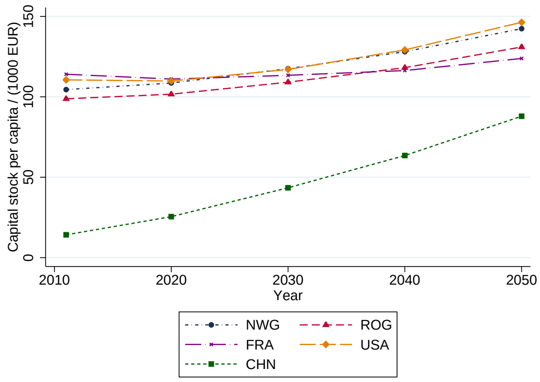
The failed transition of NWG's electricity sector is visible in its CO_2 emissions (figure C1d). While NWG reduces its CO_2 emissions to approximately 28% of the 2011 levels under FDS3 and FDS4/5, it only achieves a reduction to 36.9% under FDS1. The renewables share in electricity generation in NWG drops to 43.4% in 2020 and then to 69.8% in 2030. Thereafter, the share remains constant. Together with the absence of structural change, the low share of renewable technologies in electricity generation explains the comparatively high level of CO_2 emissions in NWG. Note, however, that the EU's CO_2 cap ensures that the total CO_2 emissions remain constant under all FDSs.

Figure C1
Results of future development scenario FDS1

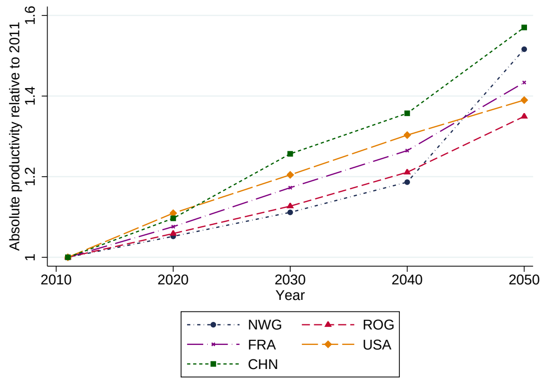
(a) GDP per capita



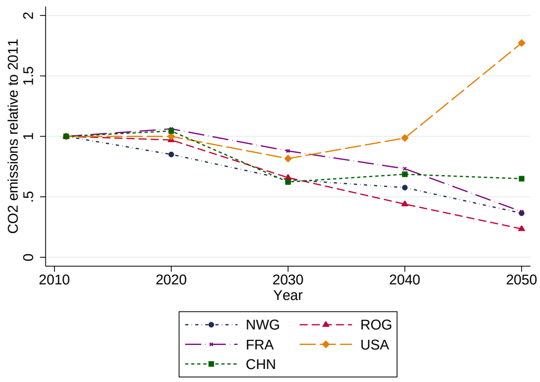
(b) Capital stock per capita



(c) Absolute productivity relative to 2011



(d) CO_2 emissions relative to 2011



(e) Renewables share

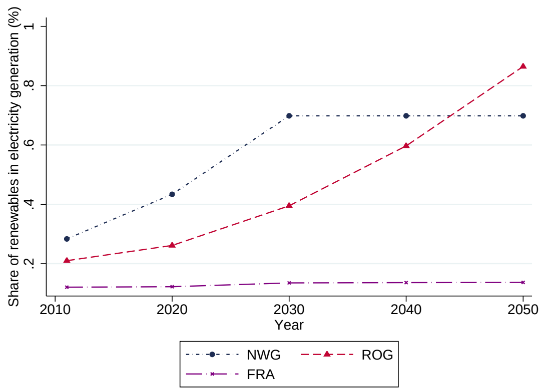


Table C1 displays further results of FDS1: the import shares of primary energy carriers in electricity generation (in per cent for year t), the share of electricity in final consumption expenditures (in per cent for year t), the change in the wage-to-capital income ratio compared to that in 2011 (in per cent), the CO_2 price in the EU ETS compared to that in 2011 (in per cent) as well as in absolute values (EUR per ton), and the welfare effect of the EU ETS (i.e., the change in real consumption compared to a baseline without European climate policy within year t in per cent).

Table C1
Results for future development scenario FDS1

	r	2020	2030	2040	2050
Import share of primary energy carriers (%)	*NWG*	12.19	12.65	11.76	12.94
	ROG	31.40	24.21	16.31	7.24
	FRA	9.61	7.86	4.75	1.43
Share of electricity in expenditures (%)	*NWG*	1.09	1.06	1.01	1.00
	ROG	1.07	1.10	1.06	1.09
	FRA	0.99	1.04	1.01	1.04
	USA	1.08	1.09	0.99	0.90
	CHN	1.32	1.38	1.29	1.28
Change in wage-to-capital income ratio (%)	*NWG*	-0.10	0.32	1.47	13.53
	ROG	0.49	0.88	1.96	4.82
	FRA	-0.45	-0.81	-0.91	-0.23
	USA	1.49	4.92	6.35	3.94
	CHN	2.14	4.78	6.18	8.50
Change in EU ETS price (%)		11.97	202.76	439.45	1287.91
(EUR/t)		15.15	40.97	73.00	187.82
Welfare change due to European climate policy (%)	*NWG*	-0.04	-0.50	-1.72	-15.81
	ROG	-0.08	-0.56	-0.95	-1.56
	FRA	-0.42	-3.06	-4.34	-5.41
	USA	0.00	0.04	0.09	0.10
	CHN	0.01	-0.25	-0.27	-0.43

The import share of primary energy carriers electricity generation and the share of electricity in consumption expenditures is expressed in per cent. The wage-to-capital income ratio and the EU ETS price are expressed in changes compared to 2011. The EU ETS price is additionally shown in EUR per ton. The welfare effect of the European climate policy is expressed as a percentage change compared to a baseline without European climate policy for year t. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.

Due to NWG's lower renewables share, the import shares of primary energy carriers are substantially higher under FDS1 than under any other FDS. They fluctuate around 12% between 2020 and 2050. The expenditure share of electricity is also higher under FDS1 than under the other FDSs, for instance, because power generators have to pay higher CO_2 prices.

From 2030 onwards, NWG's wage-to-capital income ratio is higher than in 2011 and, thus, under the other FDSs. These results suggest that workers receive gains from the combination of high growth rates and an absence of structural change. The large increase in absolute productivity found in 2050 appears to be particularly beneficial for laborers.

The CO_2 prices in the EU ETS are slightly higher under FDS1 than under FDS4/5 until 2040 because Germany does not exhibit structural change and because NWG's electricity mix contains more fossil fuel technologies under FDS1. In 2050, however, the CO_2 price is lower under FDS1 than under FDS4/5. This unexpected result is caused by the large productivity differences between FDS1 and FDS4/5 in 2050. The substantial welfare effect of the EU climate policy can be attributed to the same phenomenon.

C.2 FDS2

This subsection displays the results of future development scenario FDS2 for the baseline policy evaluation scenario PES3. Recall that FDS2 is based on assumptions similar to those of FDS3 but exhibits electricity generation in NWG that uses 100% renewable energies in 2050. The key results are presented in figures C2a to C2e.

The evolution of GDP and capital stocks per capita is identical under FDS2 and FDS3 by definition, but the sectoral absolute productivities grow less under the former FDS than under the latter. NWG's absolute productivity increases by 9.9% under FDS2 between 2011 and 2050 compared to 11.7% under FDS3. Thus, the small differences in the electricity mix of NWG lead to non-negligible differences in technological progress implied by the forward calibration process.

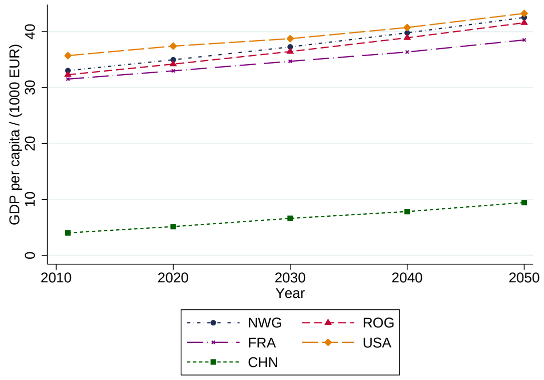
Despite the lower renewables share, NWG exhibits lower CO_2 emissions under FDS3 than under FDS2, which indicates that the differences in absolute productivity have a greater impact on emission levels than do differences in the renewables share.

Further results of FDS2 are presented in table C2. The import share of primary energy carriers in electricity generation is lower under FDS2 than under FDS3 because electricity generation relies more on renewables. The expenditure shares of electricity in final consumption are minimally lower under FDS2 than under FDS3. The wage-to-capital income ratio is also lower under FDS2 than under FDS3.

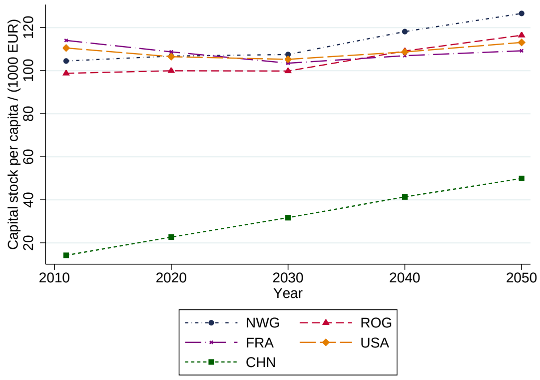
The CO_2 prices are higher under FDS3 than under FDS2, despite the lesser importance of renewable technologies in NWG's electricity mix. This indicates that the differences in absolute productivity identified by the forward calibration process have a stronger impact on climate policy than the moderate differences in NWG's electricity sector. The welfare effects of the EU climate policy under FDS2 and FDS3 resemble each other.

Figure C2
Results of future development scenario FDS2

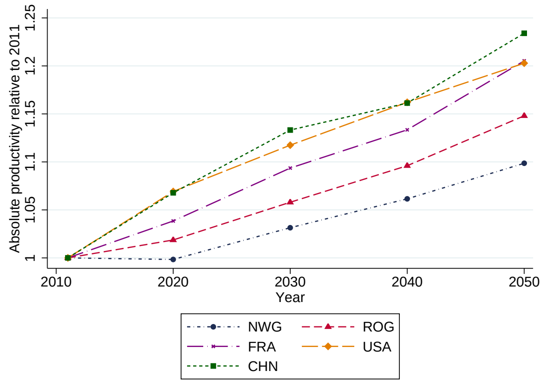
(a) GDP per capita



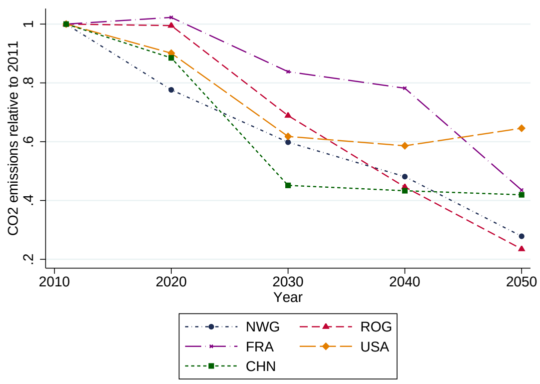
(b) Capital stock per capita



(c) Absolute productivity relative to 2011



(d) CO_2 emissions relative to 2011



(e) Renewables share

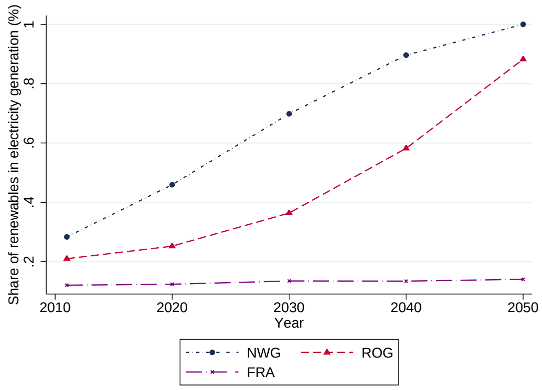


Table C2
Results for future development scenario FDS2

	r	2020	2030	2040	2050
Import share of primary energy carriers (%)	*NWG*	12.20	12.96	3.88	0.00
	ROG	31.78	25.24	16.94	5.60
	FRA	9.37	7.55	4.35	1.09
Share of electricity in expenditures (%)	*NWG*	1.12	1.05	0.92	0.95
	ROG	1.06	1.05	0.94	0.95
	FRA	0.97	0.97	0.87	0.91
	USA	1.05	1.06	0.96	0.87
	CHN	1.25	1.23	1.16	1.11
Change in wage-to-capital income ratio (%)	*NWG*	-1.77	-2.06	-0.67	0.12
	ROG	-1.49	-1.64	0.62	0.76
	FRA	-0.12	-0.51	-0.94	-0.99
	USA	0.05	2.72	4.36	4.49
	CHN	1.28	3.21	4.56	5.48
Change in EU ETS price (%)		-35.08	138.60	383.28	1380.71
(EUR/t)		8.79	32.29	65.40	200.38
Welfare change due to European climate policy (%)	*NWG*	-0.03	0.00	-0.38	-1.55
	ROG	-0.06	-0.24	-0.52	-1.59
	FRA	0.01	-1.90	-2.54	-5.63
	USA	0.00	-0.02	-0.04	0.04
	CHN	0.02	-0.19	-0.15	-0.15

The import share of primary energy carriers electricity generation and the share of electricity in consumption expenditures is expressed in per cent. The wage-to-capital income ratio and the EU ETS price are expressed in changes compared to 2011. The EU ETS price is additionally shown in EUR per ton. The welfare effect of the European climate policy is expressed as a percentage change compared to a baseline without European climate policy for year t. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.

C.3 FDS4

Future development scenario FDS4 is based on the same macroeconomic assumptions as FDS5 and thus leads to the same results (see sections 4.2.2 and 4.3.2).

D Remaining policy evaluation scenarios

Table D1
Results of the policy evaluation scenarios for FDS1

		PES1				PES2			
	r	2020	2030	2040	2050	2020	2030	2040	2050
GDP per capita	*NWG*	0.00	-0.03	-0.05	-0.06	0.00	0.03	0.05	0.07
	ROG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	FRA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	USA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CHN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Regional absolute productivity	*NWG*	-0.32	0.30	6.38	-14.43	-0.32	0.35	5.30	-16.47
	ROG	0.00	1.13	4.20	4.36	0.00	1.11	3.52	13.01
	FRA	0.00	1.34	2.63	-39.20	0.00	1.09	2.24	-39.30
	USA	0.00	-3.02	1.00	3.98	0.00	-2.64	1.59	4.46
	CHN	0.00	-0.25	4.77	-0.37	0.00	-0.18	3.99	0.01
CO_2 emissions	*NWG*	-0.85	-3.20	-1.63	-1.64	-0.90	-2.64	-0.64	-0.17
	ROG	0.04	-0.85	0.38	0.24	0.04	-0.78	0.33	-0.13
	FRA	0.01	-1.43	-0.79	0.25	0.01	-1.17	-0.52	0.39
	USA	0.00	2.00	2.87	1.56	0.00	1.73	1.90	0.80
	CHN	0.00	-2.13	-2.17	-2.12	0.00	-1.81	-1.71	-1.67
Renewables share	*NWG*	0.58	3.37	3.61	3.55	-0.80	3.79	3.52	3.57
	ROG	-0.06	0.75	-0.98	-0.41	-0.07	0.78	-0.81	-0.33
	FRA	-0.02	0.22	-0.38	3.09	-0.02	0.25	-0.33	3.19
Import share of primary energy carriers	*NWG*	-1.77	-21.86	-24.49	-19.40	-0.38	-22.96	-24.70	-19.95
	ROG	0.01	-1.85	-0.17	0.59	0.01	-1.80	-0.24	0.42
	FRA	0.08	-1.94	-0.01	0.71	0.09	-1.84	0.02	0.81
Share of electricity in consumption expenditures	*NWG*	-0.02	1.56	0.94	1.79	-0.01	0.98	0.04	1.06
	ROG	-0.01	-0.33	-0.37	-0.66	-0.01	-0.23	-0.29	-1.16
	FRA	-0.01	-0.35	-0.50	4.13	-0.01	-0.27	-0.40	4.22
	USA	0.00	-1.14	-0.69	-0.41	0.00	-0.94	-0.46	-0.34
	CHN	0.00	0.35	0.48	0.34	0.00	0.36	0.40	0.26
Wage-to-capital income ratio	*NWG*	-0.01	0.19	0.08	-1.53	-0.03	0.12	-0.05	-1.84
	ROG	0.00	-0.13	-0.10	0.44	0.00	-0.10	-0.06	1.16
	FRA	0.00	-0.01	-0.01	-0.56	0.00	-0.01	-0.01	-0.58
	USA	0.00	0.17	0.01	0.17	0.00	0.14	0.00	0.12
	CHN	0.00	0.08	0.08	0.18	0.00	0.06	0.06	0.14
CO_2 price in the EU ETS		-0.30	-4.67	-3.58	-3.08	-0.31	-3.56	-2.65	-2.68

All results for policy evaluation scenarios PES1 and PES2 are expressed in percentage changes compared to PES3 in t in per cent. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.

Table D2
Results of the policy evaluation scenarios for FDS2

	r	PES1 2020	PES1 2030	PES1 2040	PES1 2050	PES2 2020	PES2 2030	PES2 2040	PES2 2050
GDP per capita	*NWG*	0.00	-0.03	-0.06	-0.07	0.00	0.02	0.05	0.07
	ROG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	FRA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	USA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CHN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Regional absolute productivity	*NWG*	1.06	0.25	1.23	-3.16	1.18	0.15	-0.21	2.35
	ROG	0.03	0.03	0.08	-0.29	0.03	0.03	-0.06	0.22
	FRA	0.01	0.00	-0.01	0.36	0.01	0.00	0.00	0.14
	USA	0.00	0.01	0.30	0.02	0.00	0.01	-0.24	-0.10
	CHN	0.01	0.02	0.12	-0.02	0.01	0.02	-0.07	0.05
CO_2 emissions	*NWG*	-1.21	0.72	-1.39	-0.98	-1.35	0.68	4.35	1.03
	ROG	0.04	-0.03	0.03	0.02	0.05	-0.03	-0.12	-0.02
	FRA	0.02	-0.01	0.00	0.01	0.02	0.00	-0.03	-0.01
	USA	-0.01	-0.01	-0.01	-0.07	-0.01	-0.01	0.01	0.09
	CHN	0.00	0.00	0.09	0.12	0.00	0.00	-0.08	-0.09
Renewables share	*NWG*	8.66	3.35	0.00	0.00	7.74	3.80	-3.86	0.00
	ROG	-0.06	0.05	-0.01	0.00	-0.06	0.04	0.16	0.01
	FRA	-0.01	0.01	0.01	-0.01	0.00	0.00	0.01	0.00
Import share of primary energy carriers	*NWG*	-8.48	-21.02	-0.18	-	-7.47	-22.09	15.83	-
	ROG	0.00	-0.23	-0.20	-0.22	0.00	-0.21	-0.01	0.17
	FRA	0.08	-0.07	-0.04	-0.01	0.09	-0.05	-0.26	-0.06
Share of electricity in consumption expenditures	*NWG*	0.19	0.45	0.50	0.53	0.24	0.11	-0.47	-0.48
	ROG	-0.01	0.01	0.01	0.03	0.00	0.01	0.00	-0.01
	FRA	0.00	0.01	0.02	0.01	0.00	0.00	-0.01	-0.02
	USA	0.00	0.00	0.04	0.04	0.00	0.00	-0.03	-0.04
	CHN	0.00	0.00	-0.02	-0.02	0.00	0.00	0.02	0.01
Wage-to-capital income ratio	*NWG*	0.05	0.05	0.09	0.00	0.03	0.02	-0.02	-0.05
	ROG	0.00	0.00	0.01	0.00	0.00	0.00	-0.01	0.00
	FRA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	USA	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
	CHN	0.00	0.00	-0.01	-0.01	0.00	0.00	0.00	0.01
CO_2 price in the EU ETS		-0.32	0.15	0.11	0.07	-0.31	0.09	0.22	0.01

All results for policy evaluation scenarios PES1 and PES2 are expressed in percentage changes compared to PES3 in t in per cent. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.

E Policy evaluation scenarios in qualitative form

Table E1
Results of the policy evaluation scenarios for FDS1

		PES1				PES2			
	r	2020	2030	2040	2050	2020	2030	2040	2050
GDP per capita	NWG	0	-	-	-	0	+	+	+
	ROG	0	0	0	0	0	0	0	0
	FRA	0	0	0	0	0	0	0	0
	USA	0	0	0	0	0	0	0	0
	CHN	0	0	0	0	0	0	0	0
Regional absolute productivity	NWG	-	+	+	-	-	+	+	-
	ROG	0	+	+	+	0	+	+	+
	FRA	0	+	+	-	0	+	+	-
	USA	0	-	+	+	0	-	+	+
	CHN	0	-	+	-	0	-	+	+
CO_2 emissions	NWG	-	-	-	-	-	-	-	-
	ROG	+	-	+	+	+	-	+	-
	FRA	+	-	-	+	+	-	-	+
	USA	0	+	+	+	0	+	+	+
	CHN	0	-	-	-	0	-	-	-
Renewables share	NWG	+	+	+	+	-	+	+	+
	ROG	-	+	-	-	-	+	-	-
	FRA	-	+	-	+	-	+	-	+
Import share of primary energy carriers	NWG	-	-	-	-	-	-	-	-
	ROG	+	-	-	+	+	-	-	+
	FRA	+	-	-	+	+	-	+	+
Share of electricity in consumption expenditures	NWG	-	+	+	+	-	+	+	+
	ROG	-	-	-	-	-	-	-	-
	FRA	-	-	-	+	-	-	-	+
	USA	0	-	-	-	0	-	-	-
	CHN	0	+	+	+	0	+	+	+
Wage-to-capital income ratio	NWG	-	+	+	-	-	+	-	-
	ROG	0	-	-	+	0	-	-	+
	FRA	0	-	-	-	0	-	-	-
	USA	0	+	+	+	0	+	0	+
	CHN	0	+	+	+	0	+	+	+
CO_2 price in the EU ETS		-	-	-	-	-	-	-	-

All results for policy evaluation scenarios PES1 and PES2 are expressed in changes compared to PES3 in t. + indicates an increase of more than 0.05%; - indicates a decrease of more than 0.05%. 0 indicates a value between -0.05% and +0.05%. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.

Table E2

Results of the policy evaluation scenarios for FDS2

		PES1				PES2			
	r	2020	2030	2040	2050	2020	2030	2040	2050
GDP per capita	*NWG*	0	-	-	-	0	+	+	+
	ROG	0	0	0	0	0	0	0	0
	FRA	0	0	0	0	0	0	0	0
	USA	0	0	0	0	0	0	0	0
	CHN	0	0	0	0	0	0	0	0
Regional absolute productivity	*NWG*	+	+	+	-	+	+	-	+
	ROG	+	+	+	-	+	+	-	+
	FRA	+	0	-	+	+	0	0	+
	USA	0	+	+	+	0	+	-	-
	CHN	+	+	+	-	+	+	-	+
CO_2 emissions	*NWG*	-	+	-	-	-	+	+	+
	ROG	+	-	+	+	+	-	-	-
	FRA	+	-	0	+	+	0	-	-
	USA	-	-	-	-	-	-	+	+
	CHN	0	0	+	+	0	0	-	-
Renewables share	*NWG*	+	+	0	0	+	+	-	0
	ROG	-	+	-	0	-	+	+	+
	FRA	-	+	+	-	0	0	+	0
Import share of primary energy carriers	*NWG*	-	-	-		-	-	+	
	ROG	0	-	-	-	0	-	-	+
	FRA	+	-	-	-	+	-	-	-
Share of electricity in consumption expenditures	*NWG*	+	+	+	+	+	+	-	-
	ROG	-	+	+	+	0	+	0	-
	FRA	0	+	+	+	0	0	-	-
	USA	0	0	+	+	0	0	-	-
	CHN	0	0	-	-	0	0	+	+
Wage-to-capital income ratio	*NWG*	+	+	+	0	+	+	-	-
	ROG	0	0	+	0	0	0	-	0
	FRA	0	0	0	0	0	0	0	0
	USA	0	0	0	-	0	0	0	0
	CHN	0	0	-	-	0	0	0	+
CO_2 price in the EU ETS		-	+	+	+	-	+	+	+

All results for policy evaluation scenarios PES1 and PES2 are expressed in changes compared to PES3 in t. + indicates an increase of more than 0.05%; - indicates a decrease of more than 0.05%. 0 indicates a value between -0.05% and +0.05%. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.

Table E3
Results of the policy evaluation scenarios for FDS3

	r	PES1 2020	PES1 2030	PES1 2040	PES1 2050	PES2 2020	PES2 2030	PES2 2040	PES2 2050
GDP per capita	*NWG*	0	-	-	-	0	+	+	+
	ROG	0	0	0	0	0	0	0	0
	FRA	0	0	0	0	0	0	0	0
	USA	0	0	0	0	0	0	0	0
	CHN	0	0	0	0	0	0	0	0
Regional absolute productivity	*NWG*	+	+	-	-	+	+	-	-
	ROG	+	+	+	-	+	+	+	-
	FRA	+	0	-	0	+	0	-	0
	USA	0	+	+	0	0	+	+	+
	CHN	+	+	-	-	+	+	-	-
CO_2 emissions	*NWG*	-	+	-	-	-	+	-	-
	ROG	+	-	+	+	+	-	+	+
	FRA	+	-	+	+	+	0	+	+
	USA	-	-	-	-	-	-	-	-
	CHN	0	0	+	+	0	0	+	+
Renewables share	*NWG*	+	+	+	+	+	+	+	+
	ROG	-	+	-	-	-	+	-	-
	FRA	-	+	0	-	0	0	-	-
Import share of primary energy carriers	*NWG*	-	-	-	-	-	-	-	-
	ROG	0	-	-	+	0	-	-	+
	FRA	+	-	+	+	+	-	+	+
Share of electricity in consumption expenditures	*NWG*	+	+	+	+	+	+	-	-
	ROG	-	+	0	0	0	+	-	-
	FRA	0	+	0	0	0	0	0	0
	USA	0	0	+	+	0	0	0	0
	CHN	0	0	0	0	0	0	0	-
Wage-to-capital income ratio	*NWG*	+	+	+	+	+	+	0	0
	ROG	0	0	0	0	0	0	0	0
	FRA	0	0	0	0	0	0	0	0
	USA	0	0	0	0	0	0	0	0
	CHN	0	0	0	0	0	0	0	0
CO_2 price in the EU ETS		-	+	-	-	-	+	-	-

All results for policy evaluation scenarios PES1 and PES2 are expressed in changes compared to PES3 in t. + indicates an increase of more than 0.05%; - indicates a decrease of more than 0.05%. 0 indicates a value between -0.05% and +0.05%. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.

Table E4
Results of the policy evaluation scenarios for FDS4/5

		PES1				PES2			
	r	2020	2030	2040	2050	2020	2030	2040	2050
GDP per capita	*NWG*	0	-	-	-	0	+	+	+
	ROG	0	0	0	0	0	0	0	0
	FRA	0	0	0	0	0	0	0	0
	USA	0	0	0	0	0	0	0	0
	CHN	0	0	0	0	0	0	0	0
Regional absolute productivity	*NWG*	-	-	+	+	-	-	-	+
	ROG	0	+	+	+	0	+	-	-
	FRA	-	+	+	+	-	+	-	+
	USA	0	-	-	+	0	-	+	+
	CHN	0	+	+	-	0	+	-	+
CO_2 emissions	*NWG*	-	-	-	0	-	-	+	+
	ROG	+	+	-	+	+	+	+	-
	FRA	+	-	-	+	+	-	+	+
	USA	0	+	+	-	0	+	-	-
	CHN	-	-	-	+	-	-	+	+
Renewables share	*NWG*	+	+	+	0	-	+	-	0
	ROG	-	-	+	+	-	-	-	+
	FRA	-	+	+	+	-	+	-	+
Import share of primary energy carriers	*NWG*	-	-	-		-	-	+	
	ROG	0	-	-	-	+	-	+	+
	FRA	+	+	-	-	+	+	+	-
Share of electricity in consumption expenditures	*NWG*	-	+	+	+	-	+	-	-
	ROG	-	-	+	+	-	-	-	+
	FRA	-	-	-	+	-	-	+	+
	USA	0	-	-	+	0	-	+	+
	CHN	0	+	+	+	0	+	-	-
Wage-to-capital income ratio	*NWG*	-	+	+	-	-	+	-	-
	ROG	0	-	-	+	0	-	+	+
	FRA	0	+	0	0	0	+	0	0
	USA	0	+	+	+	0	+	-	+
	CHN	0	+	+	-	0	+	-	-
CO_2 price in the EU ETS		-	-	-	+	-	-	+	+

All results for policy evaluation scenarios PES1 and PES2 are expressed in changes compared to PES3 in t. + indicates an increase of more than 0.05%; - indicates a decrease of more than 0.05%. 0 indicates a value between -0.05% and +0.05%. NWG = North-West Germany; ROG = Rest of Germany; FRA = France; USA = United States of America; CHN = China.