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Summary

The main drivers of transformation processes of electricity markets stem from climate policies and changing economic environments. In order to analyse the respective developments, modelling approaches regularly rely on multiple structural and parametric simplifications. For example, discontinuities in economic development (recessions and booms) are frequently disregarded. Distorting effects that are caused by such simplifications tend to scale up with an extension of the time horizon of the analysis and can significantly affect the accuracy of long-term projections. In this study, we include information on economic discontinuities and elaborate on their influences on short-and long-term modelling outcomes. Based on historical data, we identify the impact of a high-amplitude change in economic parameters and examine its cumulative effect on the German electricity market by applying a techno-economic electricity market model for the period from 2005 to 2014. Similar changes may consistently occur in the future and we expect that a more comprehensive understanding of their effects on long-term scenarios will increase the validity of long-term models. Results indicate that policy decision making based on modelling frameworks can benefit from a comprehensive understanding of the underlying simplifications of most scenario studies.

Keywords: Scenario Analysis, Electricity Markets, Economic Development, Energy Market Modelling, Uncertainty, Macroeconomic Cycles, Electricity Production

JEL Classification: Q4, Q43

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Economic Disruptions in Long-Term Energy Scenarios – Implications for Designing Energy Policy

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Abstract

The main drivers of transformation processes of electricity markets stem from climate policies and changing economic environments. In order to analyse the respective developments, modelling approaches regularly rely on multiple structural and parametric simplifications. For example, discontinuities in economic development (recessions and booms) are frequently disregarded. Distorting effects that are caused by such simplifications tend to scale up with an extension of the time horizon of the analysis and can significantly affect the accuracy of long-term projections. In this study, we include information on economic discontinuities and elaborate on their influences on short-and long-term modelling outcomes. Based on historical data, we identify the impact of a high-amplitude change in economic parameters and examine its cumulative effect on the German electricity market by applying a techno-economic electricity market model for the period from 2005 to 2014. Similar changes may consistently occur in the future and we expect that a more comprehensive understanding of their effects on long-term scenarios will increase the validity of long-term models. Results indicate that policy decision making based on modelling frameworks can benefit from a comprehensive understanding of the underlying simplifications of most scenario studies.

Keywords:

Scenario analysis, electricity markets, economic development, energy market modelling, uncertainty, macroeconomic cycles, electricity production

Introduction

Mathematical models are tailored to address specific research questions and aim to describe the links between the main determinants of the system under investigation. In the field of energy policy assessment, market modelling approaches provide valuable insights and often form the basis for the political decision-making process.

However, the underlying assumptions on exogenous input parameters, like GDP growth or energy carrier prices, and their interdependencies can affect the validity of model-based scenario studies. As a result, the required scenario quality is high, bringing their consistency into question (Schweizer & O'Neill 2014; Weimer-Jehle 2006) and ability to comprise a vast range of contextual uncertainties when combining environmental, economic, and energy perspectives (O'Neill et al. 2014; Van Vuuren et al. 2014). However, for simplicity, the modelling frameworks applied to long-term energy system studies tend to assume *continuous (or persistent) and linear growth trends* for key factors like economic growth, energy prices, technological improvements (efficiency, learning rates) even in comprehensive studies such as those conducted by OECD/IEA (2008), Tidball et al. (2010) and WEO (2016). The further the time horizon of the modelling framework lies in the future, the more uncertainty arises in the adequacy of assuming such linear trends of key parameters. The question arises of how strongly the neglect of dynamic behaviour distorts modelling results and, thus, the validity of energy market assessments relying on modelling approaches. Although macroeconomic developments have a major impact (e.g. via declining demand for power) on the electricity market, business cycles and their interlinkage to other key factors in the electricity market are generally ignored. The existence and causal direction of the link between the main indicator of the economic activity and electricity consumption is heavily disputed (Ciarreta & Zarraga 2010; Karanfil & Li 2015; Ozturk 2010).

This article aims to evaluate the inaccuracy arising from neglecting nonlinear developments and cyclical behaviour of key parameters in modelling frameworks. By analysing disruptions in economic growth, electricity demand and commodity prices and the expansion of generation capacities within the periods under consideration, we identify the implications for scenario analyses and modelling approaches. The German electricity market will be used as an object of study. By revealing the uncertainty caused by fluctuating patterns, the presented research will contribute to improving the informative value of energy market modelling results and ultimately the effectiveness of the political decision-making process towards future transition pathways. Furthermore, it will contribute to the extensive scientific discussion on uncertainty in the field of energy market modelling.

The presented research will assess the reference period from 2005 until 2014. With the financial crises in 2007/08 that brought a significant economic disruption, this interval provides a conclusive overview of different growth and price patterns. The paper is organised as follows: Section 2 provides an overview of the concept of uncertainty and non-linearity in energy market models. Section 3 describes the methodology of our analysis and the data used. In Section 4, the results are presented and we discuss policy implications.

Background and motivation

Uncertainty in the context of energy models can be attributed to three major categories: (i) parametric (ii) structural (Price & Keppo 2017) and (iii) context uncertainty (Weimer-

Jehle et al. 2017). The first category describes uncertainty stemming from the initial input parameter data sets (Marangoni et al. 2017). Structural uncertainty refers to model specific assumptions and simplifications (Trutnevyte 2016). The third category describes the nexus of possible developments in social, political, economic and technological environments. Different approaches has been implemented to address this type of uncertainty in the climate and energy scenarios (Geels et al. 2016; O'Neill et al. 2014), as well as in the scenarios for energy intensive industries (see e.g. Vögele et al. (2019)).

Cyclical behaviour and non-linearity of the key input parameters can be interpreted as parametric uncertainty. There are already several studies investigating cycles of certain elements within energy market models. Pesch et al. (2015) analyse wind and solar time series on their cyclical behaviour. The occurrence of capacity cycles within deregulated markets, with a constant fluctuation of over- and underinvestment has been explored by various researchers (Arango & Larsen 2011; Ford 1999) and have been linked to cyclical behaviour of electricity prices. Shifts on the macroeconomic level, like economic growth or changes in interest rates, impact both the supply and the demand side of energy systems, thereby directly affecting electricity markets. In the context of business cycles, the relationship between energy (or specifically electricity) consumption and economic growth has been of constant interest (Ferguson et al. 2000; Hirsh & Koomey 2015; Narayan & Prasad 2008; Payne 2010). In that respect, the influence of commodity prices also have to be taken into account. A broad variety of research examines the link between energy commodity prices (e.g. oil prices) and economic activity (Hamilton 1996; Kyrtsou et al. 2009). These efforts stressed the importance of approaches that allow nonlinear modelling of energy commodity prices against convenient linear time series models. This study takes up the discussion and examines the impacts of high-amplitude economic discontinuities on electricity markets.

In doing so, the approach introduced in this study focuses on changes in electricity consumption as a result of changes in GDP growth, as well as on the volatility of major energy commodity prices and emission allowances. Fig. 1 depicts the volatility of energy carrier prices and emission allowances for the period under consideration.[1]

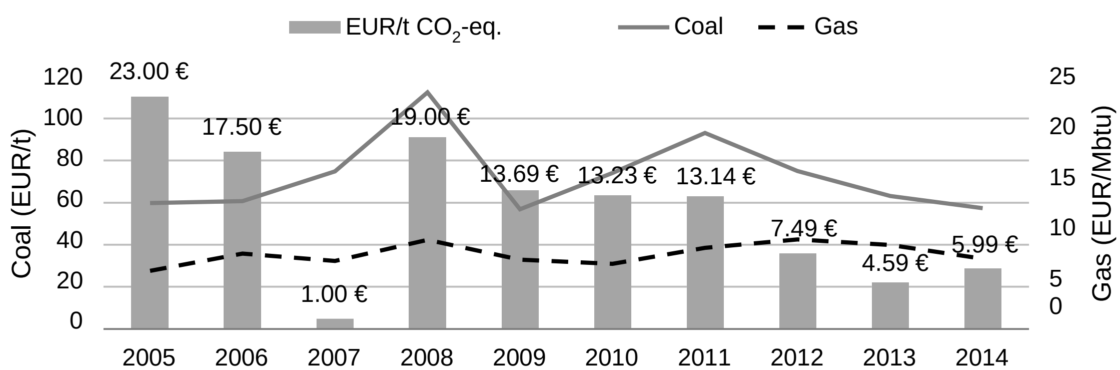


Fig. 1 Changes in main input factors: gas and hard coal prices, CO_2 certificate prices.

Sources: EUA price 2005-2008: Trends and projections in the EU ETS: (EEA 2018); EUA price 2009-2014: (EEX 2018) ; coal and gas: BP Statistical Review of World Energy (BP 2017).

Methodology

1.1 Model specifications

This study applies an the Electricity Market Model for Europe (EMME) (Vögele et al. 2018), which is a linear optimisation model that features all member states of the EU[2]. It models both dispatch and investment, by minimising total system costs (overall variable generation costs and investment costs) subject to electricity demand and a set of technical

[1] Two phases of ETS (2005-2012) produced controversial regulations and volatile CO_2 certificate prices, leading to volatile investment incentives for fossil fuel generators (Pahle, 2010).

[2] Excluding Malta, Luxembourg and Republic of Cyprus.

constraints. Equation (1) is an objective function, typical for bottom-up partial equilibrium models of the wholesale electricity market:

$$\min C = \sum_{h,i,d} \left[Pr_{h,i,d} \cdot Cst_{i,d}^{var} \right] + \sum_{i,d} \left[\left(G_{i,d}^{inv} \cdot Cst_{i,d}^{inv} \right) + \left(G_{i,d} \cdot Cst_{i,d}^{fix} \right) \right] \qquad \forall\, h, i, d \qquad (1)$$

Equation (2) describes the energy balance constraint and equations (3) to (5) present technical constraints.

$$\sum_{i} Pr_{h,i,d} + \sum_{k} I_{h,i,k} - \sum_{d} I_{h,i,d} = D_{h,i,d} \qquad \forall\, h, i, d \qquad (2)$$

$$Pr_{h,i,d} \leq G_{h,i,d} \qquad \forall\, h, i, d \qquad (3)$$

$$G_{h,i,d} \leq \left(G_{h,i,d}^{inst} + G_{h,i,d}^{inv} \right) \cdot \alpha_{h,i,d} \qquad \forall\, h, i, d \qquad (4)$$

$$I_{h,i,d} \leq NTC_{d,k} \qquad \forall\, h, i, d \qquad (5)$$

where:

h	specific hour of the year [-]
i	technology index [-]
d and k	country indexes [-]
$Cst_{i,d}^{var}$	variable generation costs [€/MWh]
$Cst_{i,d}^{fix}$	quasi-fixed annual costs (e.g. labour costs) [€/MW]
$Cst_{i,d}^{inv}$	investment costs (annuity recalculated from overnight costs) [€/MWe]
$Pr_{h,i,d}$	electricity production [MWh]
$G_{h,i,d}$	total generation capacity [MW]
$G_{h,i,d}^{inst}$	installed generation capacity at the beginning of the period [MW]

$G_{h,i,d}^{inv}$	invested generation capacity of gas, lignite and coal [MW]
$\alpha_{h,i,d}$	technical availability factors for conventional technologies, or time series for variable technologies [-]
$I_{h,i,k}$	electricity imports from the country k and $I_{h,i,d}$ electricity exports of the country d [MWh]
$D_{h,i,d}$	electricity demand [MWh]
$NTC_{i,k}$	net transfer capacity between two countries [MW]

In the dispatch mode, the model is calibrated for the period 2005-2014 so that yearly runs deliver results close to reality, with regard to the overall dispatch structure (~6 % of deviation between the statistic and the output data for each technology type), CO_2 emissions and wholesale electricity prices. In the investment mode, the model takes decreases in the installed capacities (divestment) exogenously from statistics data that take the vintage structure of the power plant stock into consideration (EC 2016; ENTSO-E 2018; Eurostat 2018). The vintage structure deployed in the model allows for an accurate account of respective technical factors. In order to exclude disruptions of policy-driven changes in RES capacities (PV and wind), they are accounted for exogenously. Hence, the investment model focuses mainly on the capacity additions in gas and coal power plants (Pahle 2010).[3]

1.2 Scenario specification and key drivers of the analysis

In order to assess the implications of assuming linear trends for selected key factors instead of considering their fluctuations, we analyse the period between 2005-2014. This

[3] Although, the expansion of these capacities is to some extent also driven by energy policies (see e.g. Pahle (2010)), the authors exclude this connection in the presented study.

interval provides a conclusive overview of business cycles, with economic growth (January 2005 until May 2008), recession (May 2008 until April 2009), and timid growth/recovery (April 2009 until July 2010) (Chevallier 2011). In our analysis, we focus on Germany. In its efforts to liberalise and integrate the European electricity markets while fostering low-carbon environmental and energy policies (see e.g. (Jamasb & Pollitt 2005; Serrallés 2006).

In the dispatch mode, we aim to investigate and quantify the effects of high-amplitude changes in macroeconomic input parameters within the defined modelling framework. We test the sensitivity of the model for one 10-year (2005-2014) and two 5-year (2005-2009-2014) intervals, assuming a linear growth pattern of main economic input parameters within the respective intervals (see Tab. 1). The scenarios applied in this framework can be distinguished by their temporal resolution. In a first *annual* scenario, we calculate CO_2 emissions, wholesale electricity prices in hourly resolution and producer surpluses, using historical statistical values for key input factors (BP 2017; IEA 2015). In a second step, we compare this scenario with two scenarios based on averaged data for a *2 periods* scenario (Ia, Ib) and a *1 period* scenario (II).

Tab. 1 Key assumptions behind the scenarios

Scenario	**Annual changes**										**Scenarios with linear growth [% p.a.]**		
											Ia	**Ib**	**II**
Designation:	"annual"										"2 periods"		"1 period"
Time/Period	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2005-2009	2010-2014	2005-2014
Fuel prices													
Gas [€/mil Btu]	4.1	5.6	5.7	8.2	6.2	6.1	7.6	8.6	8.0	7.0	5.6	-0.7	2.1
Oil [€/bbl]	53.9	61.8	61.2	74.2	49.7	63.9	85.4	90.8	84.3	75.5	-2.0	8.7	3.8
Coal [€/t]	43.0	45.6	63.1	104.9	51.3	70.2	88.3	72.6	61.3	57.9	0.02	-5.3	7.1
Growth rate GDP [%]													
Germany	0.71	3.7	3.2	1.08	-5.62	4.08	3.66	0.49	0.49	1.60	0.53	2.0	1.37
United Kingdom	2.97	2.50	2.56	-0.63	-4.33	1.92	1.51	1.31	1.91	3.07	0.01	1.9	1.07
Change in installed capacity [Δ%, 2005=1] *													
Germany	HC 0 LI 0 G 0	HC-2.5 LI -0.6 GS 2.8	HC-0.5 LI 2.5 GS 3.3	HC 0.8 LI 1.8 G 10.3	HC-1.3 LI 2.2 G 12.2	HC 2.6 LI 3.3 G 15.2	HC 2.7 LI 13.3 G 15.6	HC 1.4 LI 10.3 G 27.9	HC-0.8 LI 5.2 G 29.6	HC-0.8 LI 6.2 G 30.4	HC -0.32 LI 0.54 G 2.9	HC 0.1 LI 0.77 G 3.0	HC -0.08 LI 0.67 G 2.9
United Kingdom	HC 0 G 0	HC 3.9 G 2.1	HC 5.8 G 0.2	HC 0.9 G 6.6	HC 0.9 G 10.0	HC 1.0 G 27.6	HC-2.3 G 21.6	HC -12 G 31.8	HC -28 G 30.0	HC -34 G 26.0	HC -0.23 G 2.42	HC -8.24 G 2.74	HC -4.57 G 2.6

*: HC – hard coal; LI – lignite; G – gas.

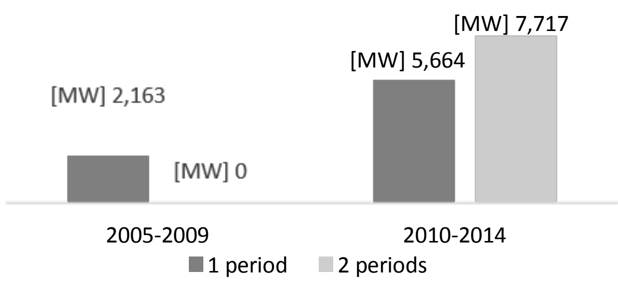
In the investment mode, we test how these underlying assumptions affect the results of the introduced investment model. We model short-term market equilibrium following the approach presented in Hirth & Ueckerdt (2013) and the investment decision on the expansion of the generation capacities of gas, coal and lignite power plants is determined on a yearly basis.

Results

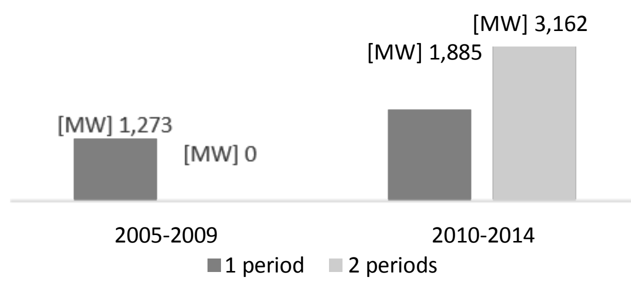
The main model outputs for each scenario differ with respect to the timing and magnitude of investments, prices and CO_2 emissions (see Tab. 1). We experience differences in the distribution of investments within the periods as shown on the Fig. 2 below.[4] Under the given assumptions, no investment occurred from 2005 to 2009 for the *2 periods* scenario

[4] The detailed overview of annual investment patterns is provided in Appendix A.

that takes into account the developments in fuel prices and demand in 2009, and takes this year as a reference point for future projections. The *1 period* scenario shows comparatively lower investments between 2010 and 2014. To trace back the underlying reasons, it is necessary to analyse the data provided by the dispatch model more precisely.



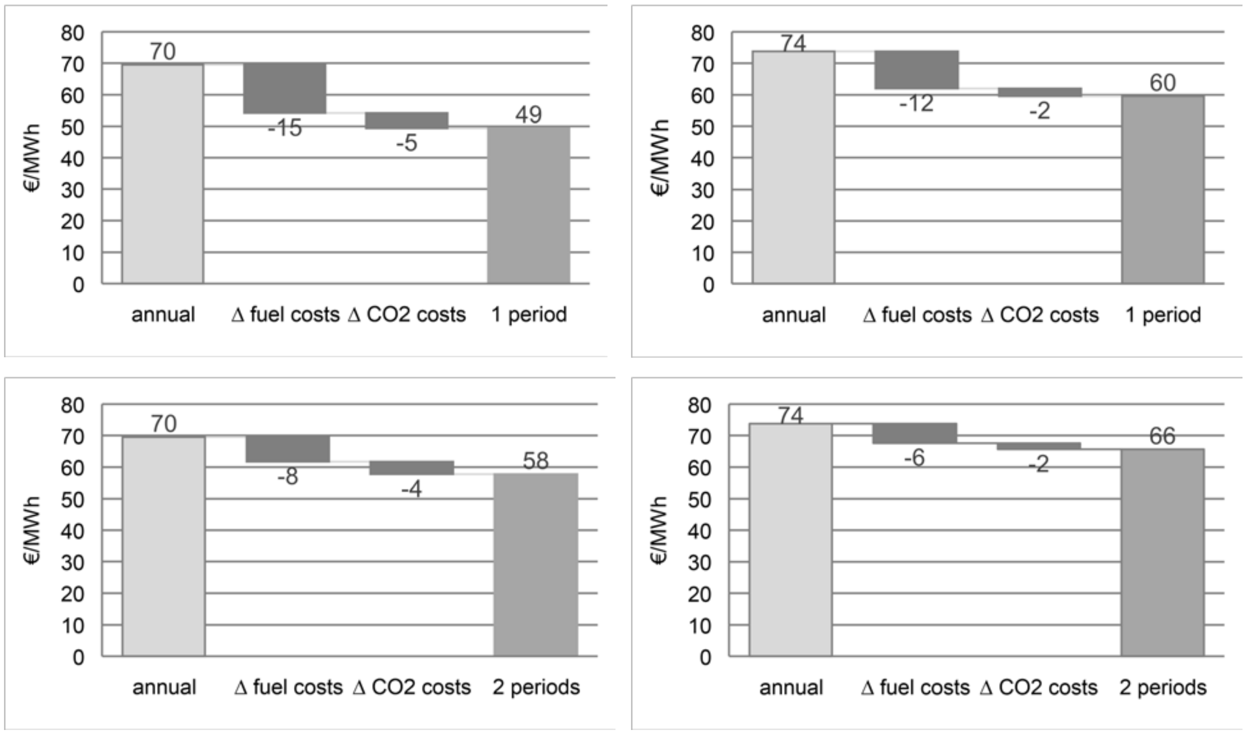
(a) Investment in coal-fired capacities in two periods (model results).



(b) Investment in gas-fired capacities in two periods (model results).

Fig. 2 Changes in the coal and gas capacity investment patterns.

A simplification of main input parameters describing the evolution of fuel prices and prices for emission allowances directly affects the composition of generation costs for the different power plant types. Consequently, their position in the merit-order will change significantly, resulting in a shift in the corresponding full-load hours. This can be illustrated by investigating generators´ typical mid and peak load variable costs for the year 2008 as depicted in Fig. 3. A decrease of 21% and 11% in generation costs, respectively, for a typical mid-load generator (a), resulted from a change in fuel prices (see Fig. 1), averaged between 2005 and 2009 for the *2 periods* scenario, and in 2005-2014 for the *1 period* scenario. These averaged values do not capture the high spike of coal and gas prices, accompanied by high prices for allowances at the beginning of the second ETS period. For base-load coal-fired power plants, this difference varies more strongly in comparison with gas power plants (b), since the relative share of emission costs (in the form of ETS certificates) within the overall generation costs is higher.



(a) Average variable costs (€/MWh) for typical mid-load power plant (here: hard coal).

(b) Average variable costs (€/MWh) for typical peak-load power plants (here: CCGT).

Fig. 3 Decomposition of changes in the input variable generation costs in the three scenarios in 2008.

The structure of the generation mix and technology specific investment costs in combination with variable costs are the major drivers for investment decisions at the assumption of perfectly competitive electricity markets. The illustrated changes in the variable generation costs due to different assumptions on fuel and environmental costs determine the combined effect on the electricity price. To emphasise the difference between the three scenarios, we consider average wholesale prices for each year of the considered time-period (see Fig. 4). The *annual* scenario delivers prices that are close to statistical spot market data. The spot market price was the highest among the years in 2008, reflecting the combined impact of changes in fuel prices and emission allowances.

The *1 period* and *2 period* scenarios are not able to capture these dynamics.[5] Changes in the cumulative CO_2 emissions inside the defined time-periods are another source of miss-interpretation in the long-term scenarios. Fig. 5 presents the CO_2 emissions for the three scenarios. While the *1 period* scenario largely exceeds the *annual* scenario's emissions, the *2 periods* scenario underestimates the amount of CO_2 emissions. The illustrated discrepancy is a result of diverse assumptions on the main input parameters that smooth developments in commodity prices, demand, changes in the expansion of the generation mix, economic growth, and trade between the regions.

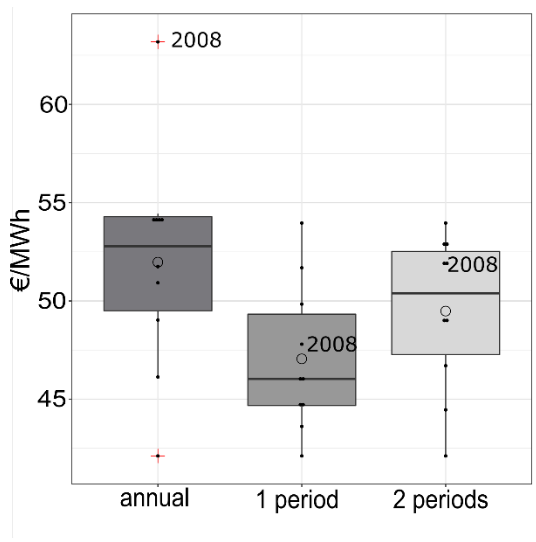


Fig. 4 Distribution of annual average electricity prices in three scenarios for each year between 2005-2004, where an "o" and a solid band inside the box denotes an average and the median respectively.

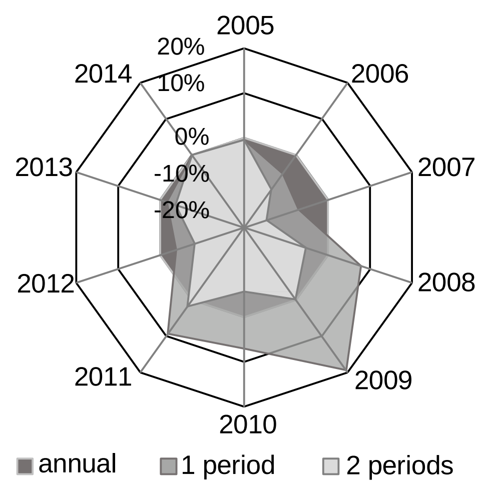


Fig. 5. CO_2 emissions from fuel combustion for electricity generation in three scenarios, where *1 period* and *2 periods* scenarios are given as ratios to the *annual* scenario, which is set to 1.

In order to investigate the reasons behind the changes in the CO_2 emissions presented in Fig. 5, we apply a decomposition analysis. Our analysis is based on the Logarithmic Mean Divisia Index (LDMI) approach described by Ang (2004), while the additive decomposition

[5] For annual average wholesale electricity prices refer to Appendix B.

analysis model implemented in the current study relates to the approach introduced by Karmellos et al. (2016). The combined effect of all factors on the total change in CO_2 emissions C_t defined in equation (6) provides perfect decompositions without residual terms in equation (7). It accounts for the activity effect A_t that reflects changes in electricity consumption due to changes in economic growth. The electricity intensity effect I_t, explained as the ratio of electricity consumption to GDP, describes the decreasing or growing share of electricity used for the domestic production. The electricity trade effect T_t categorises countries as net exporter if $T_t > 1$, or net importer if $T_t < 1$. The energy efficiency effect $e_{i,t}$ shows how technology-specific changes in the energy efficiency of the generation sector benefit from the decrease of CO_2 emissions. This effect is highly sensitive to the technology data of each power plant type featured in the model and to the assumed vintage structure. The change in CO_2 emissions between the base year (here 2014) to the year t is decomposed into the four factors described above as given in the equation (7).

$$C_t = A_t \frac{EC_t}{A_t} \frac{EP_t}{EC_t} \sum_i \frac{F_{i,t}}{EP_{i,t}} = A_t I_t T_t \sum_i e_{i,t} \quad (6)$$

$$\Delta C_{0-t} = C_0 - C_t = \Delta A_{0-t} + \Delta I_{0-t} + \Delta T_{0-t} + \Delta e_{0-t} \quad (7)$$

where:

t	index for time period [-]
i	index for generation technology [-]
C_t	total change in CO_2 emissions [Mt]

A_t	gross domestic product (GDP) for year t [billion Euro[6]]
EC_t	electricity consumption[7] [GWh]
EP_t	total electricity production in the country from all sources [GWh]
$EP_{i,t}$	electricity generated from fuel i respectively
$F_{i,t}$	amount of fuel input i for a respective generation type [GJ]

The results of the decompositions analysis for each year relative to the base year 2014 for the three scenarios are presented in Appendix C. Considering the pattern of CO_2 emissions given in Fig. 5, the year 2009 reveals a dramatic difference between the *1 period* and the *annual* scenario. However, since 2009 represents a pillar year for the calculation of the average growth rates for the *2 period* scenario, it is unsuitable for the decomposition analysis (see Tab. 1). Thus, the year 2008 will be used for the illustration of the decomposed effects (see Fig. 6).

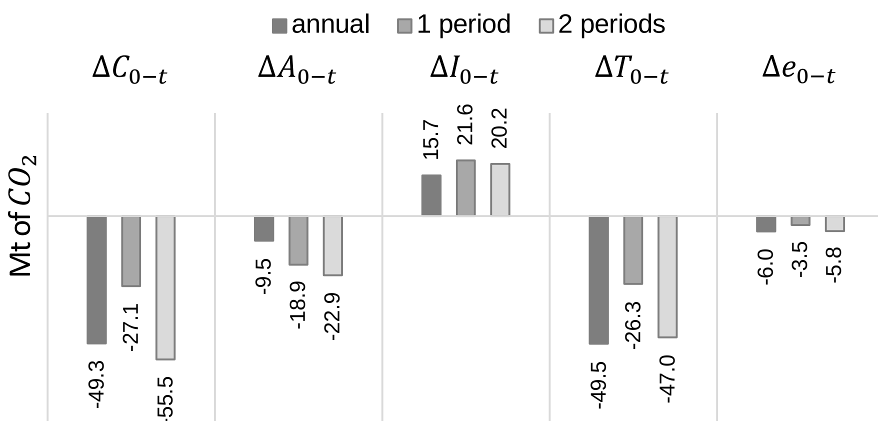


Fig. 6 Decomposition of changes in CO_2 emissions from fuel combustion in the electricity sector comparing 2014 (0) to 2008 (t).

[6] Constant Euro 2014.

[7] Statistics data for *annual* scenario (Eurostat, 2018) and data for *1 period* scenario with average electricity consumption growth from 2005 to 2014, and for *2 periods* scenario respectively.

The change in the activity effect ΔA_{0-t} in *1 period* and 2-periods scenarios has a higher impact on the increase in CO_2 emissions in 2008 relative to 2014 than the *annual* scenario. This is an effect of averaging the GDP growth from 2005 to 2009 (0.53 % p.a.), and from 2005 to 2014 (2 % p.a.). Whereas, the nominal GDP grew steadily from 2005 (2.4 billion 2014€) to 2008 (2.6 billion 2014€), and dropped by 6.7 % in 2009, almost returning to the level of 2005 (Eurostat 2018). The disregard of this discontinuity in economic growth has a significant effect on the estimation of the cumulative emissions in the period 2005-2014. Another substantial aspect is highlighted by the change in the electricity trade effect ΔT_{0-t}. In the period 2005 to 2014, Germany's electricity exports to neighbouring countries increased constantly, thus ΔT_{0-t} is negative, comparing the base year 2014 with 2008. Considering the average price developments shown in Fig. 4 for the *1 period* scenario, the trade effect is nearly 47 % less than for the *annual* scenario. Model results indicate that the price effect stimulates domestic electricity production. As a result, exports rise and CO_2 emissions in the exporting country increase significantly.

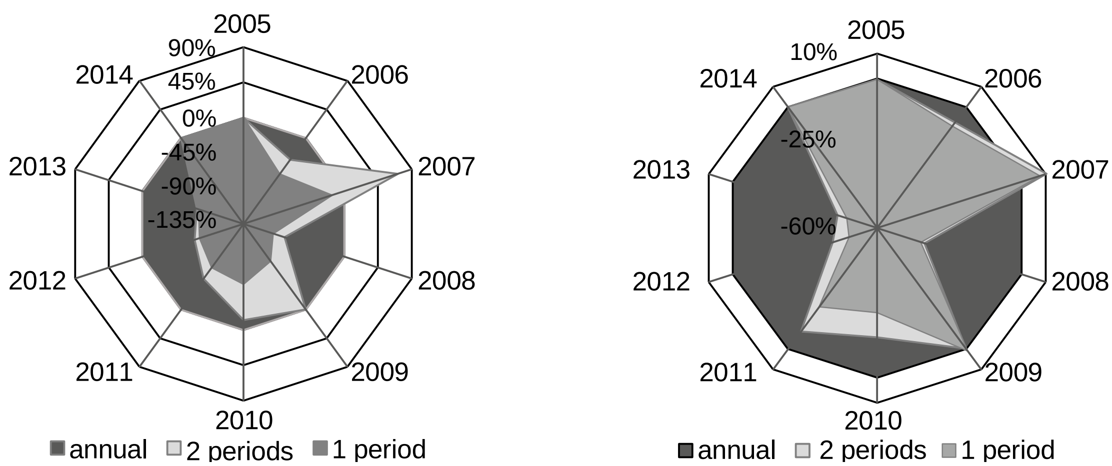


Fig. 7 Producer surplus.

Fig. 7 displays producer surpluses for the period from 2005 to 2014 (indexed to the *annual* scenario). The results suggest that surpluses for gas and coal-fired power plants are not sufficiently captured by the presented model setting. The misinterpretation of model results that reveal potential losses or gains for producers, which do not reflect the actual market conditions, may lead to inaccurate projections for future capacity expansions, attractiveness for certain technology types, or disregarding possible windows of opportunities for niche technologies.

Conclusions and policy implications

Long-term projections for energy markets in general and the electricity market, in particular, can be improved by incorporating the effects of major economic disruptions. Thus, a better understanding of the interpretation of modelling results can be formed by considering those disruptions in scenario studies. By investigating the response of the German power market to the recent economic downturn, this work contributes to a comprehensive understanding of long-term risks, their possible sources and the magnitude of their impacts.

As shown, the assumption of linear growth within the period under consideration leads to a significant underestimation of generation costs. However, by considering two time periods, the resulting generation cost assumptions for mid- and peak load power plants converge substantially closer to the annual data than the 10-year averages. On the one hand, the divergences of actual and modelled generation costs could lead to a major overestimation of profit opportunities for generators or, on the other hand, an underestimation of future wholesale electricity prices. This relationship might lead to false assessments of investment incentives for certain generation technologies.

An inaccurate estimation of producer surpluses (as shown in Fig. 7) for specific generation technologies might lead to false conclusions with regard to the future need for policy intervention. The timing and implementation of environmental regulations significantly affect investment decisions as well. The combined effects of policies and market design shape the investment decisions for electricity generators. Therefore, if disruptions in macroeconomic factors are not taken into consideration, policy measures aiming towards energy transition may not be conceived in time or be insufficient.

Considering the pattern of CO_2 emissions for the studied period, our results suggest that carbon budgets will not be described sufficiently by analogous modelling frameworks. In the presented period, the divergence between the overall CO_2 emissions of the annual scenarios and the 1 period and 2 period scenario amounts to nearly -54 Mt and +114 Mt respectively. Thus, the approach of assuming linear growth rates for key parameters promotes a misleading picture of the techno-economic background, overlooking the need for emerging technologies in order to achieve certain environmental goals (e.g. meeting CO_2 budgets). The experienced inaccuracies might result in ineffective policy measures, based on the gap between the expected and actual generation costs, fuel prices, electricity demand and economic growth. As a consequence, if dynamic economic developments are not taken into consideration during the policy planning process, the need for further policy intervention in order to shape the design of the future electricity sector can be drastically misjudged. Consequently, the design of energy policy measures, that are based on modelling frameworks, may prove inefficient or ineffective, if economic disturbances are not considered within the scenario analysis. While we are not able to precisely predict forthcoming economic disruptions, we do know that they will occur. Thus, for future policies it is necessary to have a better understanding on how to interpret long-term power scenarios to take into account abrupt changes in the pace of economic growth. By implementing statistical data of the economic crises in 2008 and assessing its implications on the German power sector, this study provides novel insights into the impacts of economy-wide disruptions on energy systems. We conclude that the validity of policy assessments based on scenario studies for energy systems can be improved if the occurrence of such events is taken into consideration.

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Appendix A

Investment patterns

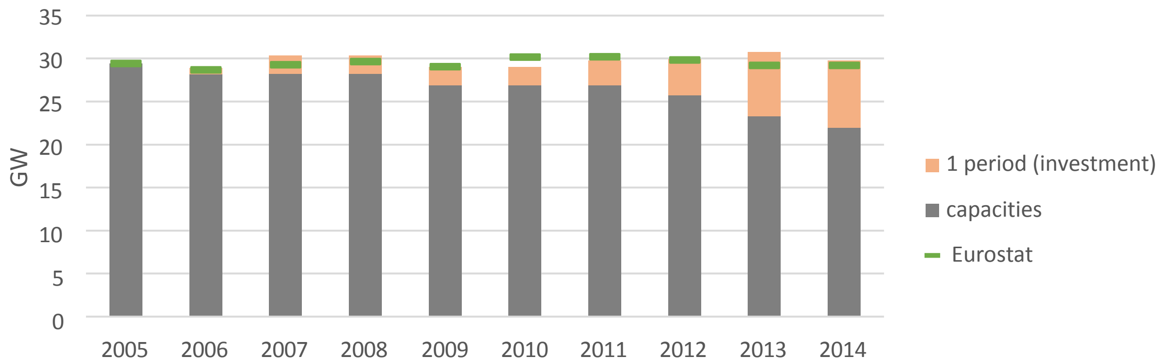

Fig. A.1 Investment in coal-fired capacities in the period 2005-2014 (model results).

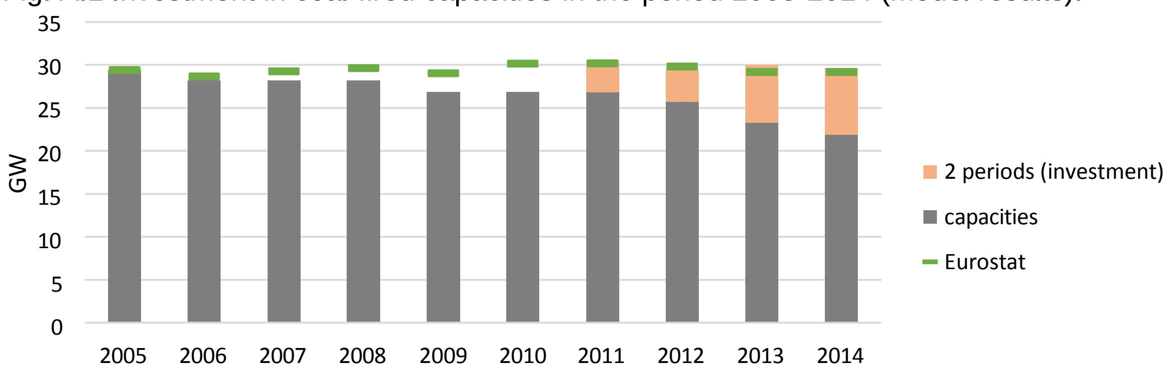

Fig. A.2 Investment in coal-fired capacities in the period 2005-2014 (model results).

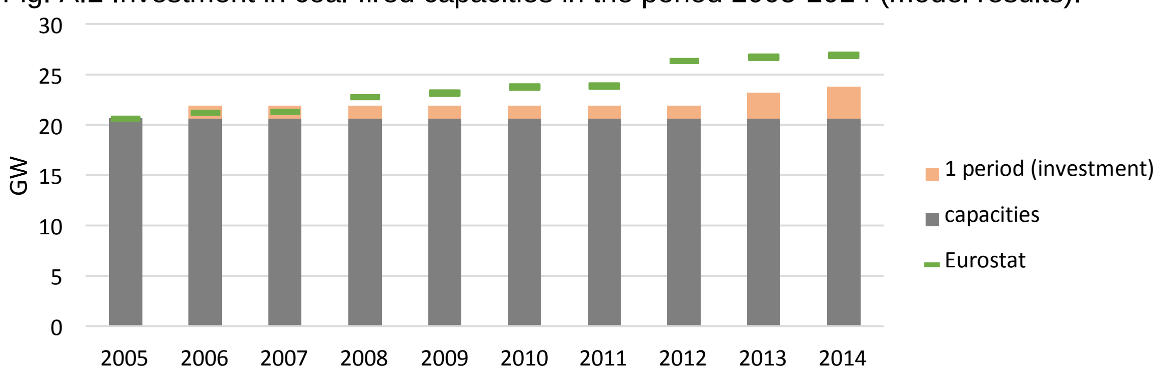

Fig. A.3 Investment in gas-fired capacities in the period 2005-2014 (model results).

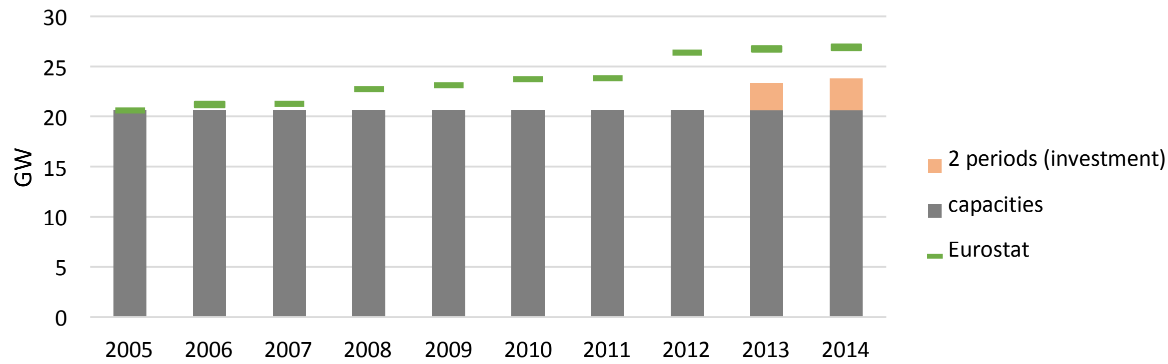

Fig. A.4 Investment in gas-fired capacities in the period 2005-2014 (model results).

Appendix B

Average electricity prices

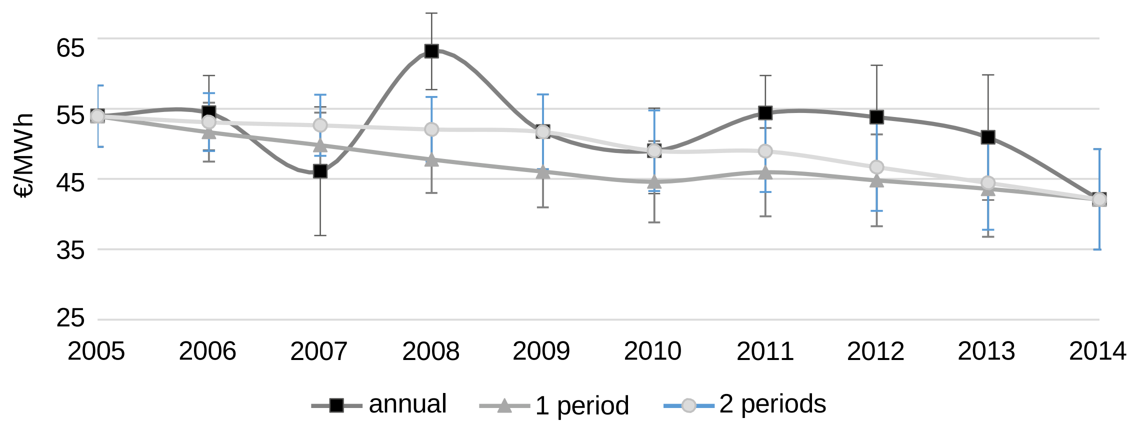

Fig. B.1 Average electricity prices (model results).

Appendix C

Decomposition analysis

Tab. C.1 Results of the decompositions of changes for the *annual* scenario.

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
C_t	-91.8	-46.5	-13.3	-49.3	-57.3	-27.6	-18	19.3	9.84	0
A_t	-23.8	-19	-12.9	-9.54	-21.6	-14.2	-6	-5.26	-3.95	0
I_t	27.4	25.4	20.4	15.7	15.1	22.8	11.7	11.6	8.93	0
T_t	-71.8	-50.6	-23.2	-49.5	-48	-35.4	-23.2	9.36	3.07	0
e_t	-23.6	-2.28	2.42	-5.96	-2.72	-0.79	-0.58	3.55	1.79	0
Σ	-91.8	-46.5	-13.3	-49.3	-57.3	-27.6	-18	19.3	9.84	0

Tab. C.2 Results of the decompositions of changes for the *1 period* scenario.

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
C_t	-92.6	-63.7	-37.4	-27.1	-16.8	-11.3	8.3	8.1	5.4	0
A_t	-23.8	-23.0	-21.5	-18.9	-16.1	-13.0	-10.2	-6.8	-3.4	0
I_t	27.2	26.5	24.7	21.6	18.5	15.0	11.7	7.8	3.8	0
T_t	-72.2	-53.8	-34.5	-26.3	-18.9	-15.5	4.7	5.4	4.0	0
e_t	-23.8	-13.4	-6.1	-3.5	-0.2	2.3	2.1	1.6	1.0	0
Σ	-92.6	-63.7	-37.4	-27.1	-16.8	-11.3	8.3	8.1	5.4	0

Tab. C.3 Results of the decompositions of changes for the *2 periods* scenario.

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
C_t	-92.6	-72.6	-55.4	-55.5	-57.4	-40.6	-7.69	-2.58	0.51	0
A_t	-23.8	-24.1	-24.1	-22.9	-21.6	-18.1	-14.7	-9.88	-4.97	0
I_t	27.2	25.7	23.6	20.2	16.6	14	11.3	7.58	3.86	0
T_t	-72.2	-59.4	-47.1	-47	-49.7	-36.6	-6.9	-2.13	0.63	0
e_t	-23.8	-14.8	-7.88	-5.85	-2.74	0.16	2.52	1.85	0.99	0
Σ	-92.6	-72.6	-55.4	-55.5	-57.4	-40.6	-7.69	-2.58	0.51	0

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