A System Dynamics model for the German Electricity Market –

An analysis of economic and environmental policy related impacts on electricity prices and CO_2 emissions

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Abstract:
The objective of this paper is to show the intensity of the impacts of various economic and environment related policy frame conditions on the development of electricity market prices for Germany and the performance of CO_2 emissions. For this analysis a dynamic simulation model for the German electricity spot market was developed by EIFER, called "Zertsim". This techno-economic model, based on the methodology of System Dynamics, is able to depict complex and dynamic relations of an (energy) system by use of causal loops for the presentation of short, medium and long term effects on each variable in the model. Due to description of complex causal relations, fast model runs and visual presentations which are easy to understand, the model is able to provide information in particular for decision making processes in corporate planning. A first application of the model was made in a workshop under participation of representatives of the industry and science from the region of Karlsruhe in Germany, who estimated the values for demand, fuel prices for coal and natural gas, CO_2-tax and feed-in tariffs for renewable energies as the main input variables. The outcome of the model calculations were eight scenarios for the future development of the electricity system in Germany. Main results were that the implementation of high environmental taxes and feed-in tariffs for renewable energies leads to the highest electricity prices and the highest reduction of CO_2- emissions. Furthermore the extension of operating hours of nuclear power plants in Germany allows constant electricity prices on a relatively low level. An increasing demand for electricity by 1,5%/a leads in the case of a nuclear phase out for Germany to the highest prices compared to all scenarios in the years 2021 to 2026. Comparing the impacts in all scenarios with respect to electricity prices and CO_2 emissions, the most determining factors for high electricity price levels for the entire time horizon between 1998 and 2026 are: 1) environment related policy instruments (High prices for CO_2 emissions, high feed-in tariffs), 2) fuel prices, 3) demand for electricity, and finally 4) extensions of the operation time for nuclear power stations in Germany. Regarding CO_2 emissions the highest impacts could be find in case of: 1) environment related policy instruments, 2) extension of operation time for nuclear power stations in Germany, 3) demand for electricity and finally 4) fuel prices.

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1 Introduction

In the field of energy system analysis, different models can be used by analyzing complex systems for appropriate and transparent decisions. Examples for such complex issues are the relations between climate change, market liberalization, globalization, measures in energy and environmental policy and energy systems.
In this paper, an application of a simulation model, based on the system dynamics methodology will be presented. The model provides information for decision making processes in corporate planning.
Starting with a short description of the dynamic simulation model for the German electricity market, the main focus of the paper is the application of the model. As a good example of how system dynamics may be used, results from a model calculation at a workshop in collaboration with corporate representatives are presented. The results were 8 scenarios concerning possible developments of the electricity market in Germany in the period of 1998 to 2006. Aim of the scenario creation was the impact study of economic and environmental constraints for the electricity market of Germany regarding electricity prices and CO_2 emissions.

2 Methode: System Dynamics

System dynamics was developed during the 1960s by Jay F. Forrester and became a powerful methodology for analyzing and simulating complex feedback systems (Forrester 1961). The simulation of different scenarios promotes the understanding for dynamic behaviour of systems over time. The main elements of the system dynamic method are variables in mathematic equations, presenting stocks and flows as well as causal relations. They are represented by the use of short-, medium-, and long term causal loops. Thereby, variables are connected together in feedback loops.

3 Das „Zertsim“ Modell

The dynamic simulation model introduced in this paper is used to simulate the effects on structure and system behaviour on the electricity market in Germany. Recommendations for action and decision support can be derived, when considering the impacts of different economic framework conditions (demand for electricity) or different environmental policy instruments (CO_2-tax, feed-in tariffs for renewable energies) on electricity prices and on capacity development, CO_2 emissions and electricity production in the electricity sector.

The objective of the simulation model “Zertsim” is in particular the analysis of short and long-term price behaviour (spot market price and the average price) of the electricity market. This is especially the consequence of different energy- and environmental policies. EIFER developed in an initial step the dynamic simulation model “Zertsim” for the analysis of the electricity market in Germany. It is considered in the model a time period for the analysis from 1998 until 2026. The model is based on a thesis from K. Vogstad, who developed a comparable model for the electricity market of the Nordic countries (Vogstad 2004).

A current version of “Zertsim“ (Date: December 2008) enables short time calculations of approx. one minute. The model allows due to the variation of input parameter and the immediate presentation of results, the support of discussions about the future of electricity markets in workshops. In addition, the model is suitable for decision support of investments in decentralized and renewable energies of the user. “Zertsim” was developed with the software VENSIM©, which provide a large graphic support for programming as well as during representing results.

4 Model properties

In the following table below specific model properties of the dynamic simulation model „Zertsim“ are presented.

Table 1: Overview about model properties of the model „Zertsim“

MODEL PROPERTIES	“ZERTSIM”
Model type	Dynamic simulation with the methodology System Dynamics, myopic
One economic sector model	Electricity sector
Approach	Descriptive
Techno-economic	Description of technologies on the level of energy carriers and transforming technologies (Uranium, oil, natural gas, gas peak turbines, gas CCS, hard coal, hard coal CCS, lignite, hydropower, biomass, biogas, wind onshore, wind offshore, photovoltaic)
Model approach	Bottom-up, supply side orientated
Technological progress and re-source availability	Partially endogenous
Multi-periodic/ time horizon	In annual steps, 1998 - 2026
Graphical scope	National, Germany, (one international connection to the rest of Europe)
Environment related policy in-struments	CO_2-tax, feed-in tariffs, optional: Nuclear phase out/ or not.
Demand side	Aggregation of load curve, no distinction of eco-nomic sectors (like industry, tertiary, transport etc.)
Behaviour of market actors	No distinction between individual actors with indi-vidual behavioural functions

In the model « Zertsim » the German electricity market is modelled through short-, medium- and long-term feedback loops. This model type allows visualizing causal relations among interrelated variables and shows how one variable affects another. An example is the implementation of the CO_2 tax and the effect on electricity prices.

Figure 1 illustrates direct and indirect effects as well as their different time horizons. Thus, supply and demand affect each other in a short-term behaviour, while technical progress and resource availability affects electricity prices on a long-term basis.

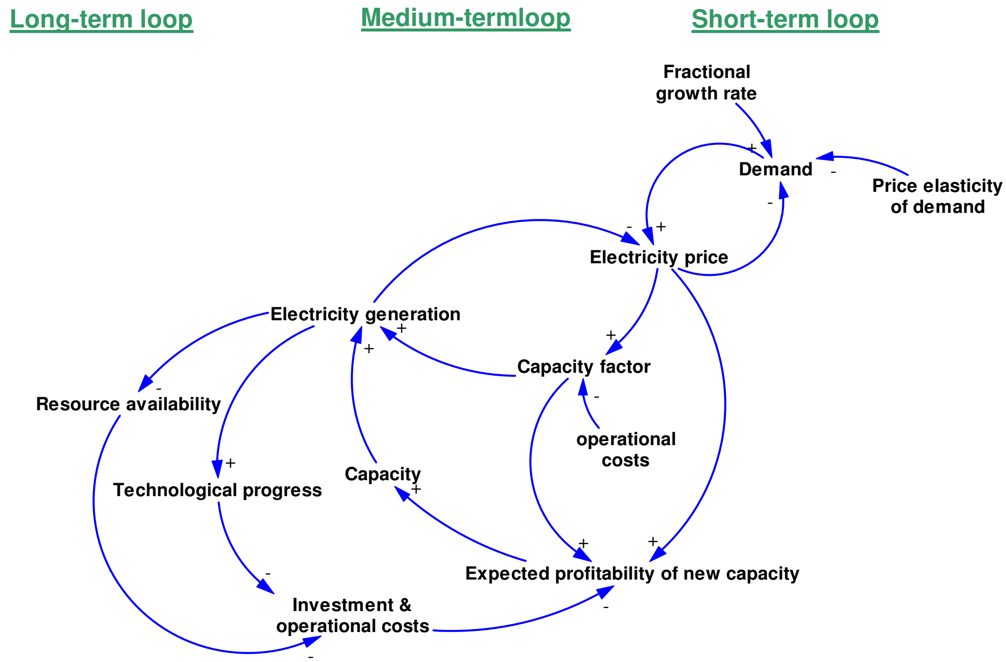

Figure 1: „Causal loop diagram“, Core model of „Zertsim“ (own illustration)

The dynamic mechanism of the model ables to identify time delays and market imperfections, which can temporarily lead to market disequilibria. In addition, adjusting market equilibria on a long term basis are a potential result of policies and model structure. Market equilibria are not a model assumption like in Linear Programming (LP-) models.

Because of the dynamic market mechanism, “Zertsim” is a myopic model with a time horizon of two years. In addition the model does not contain perfect foresight. The temporal development of input parameters over the entire considered period is determined by the initial value and decision rules. Therefore for example the capacities of each technology for electricity production are the result of development over time and not necessarily optimal with respect to costs.

5 Model validation

A first validation of the model “Zertsim” was done with regard to “electricity capacities” and the “produced quantities of electricity” (Figures 2 and 3).

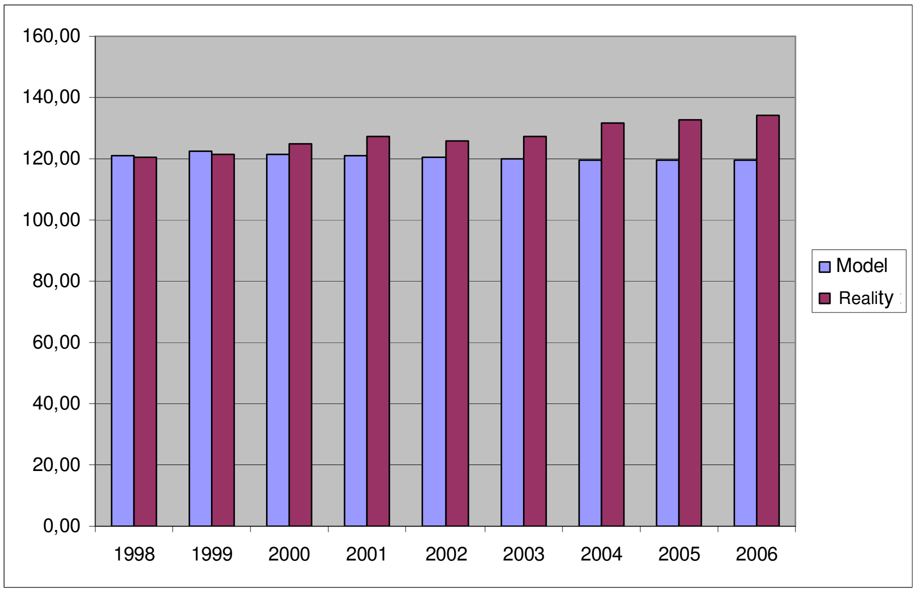

Figure 2: Electricity capacities in the years 1998 - 2006

Electricity capacities for Germany in the model deviate from reality between 0,4 % und -11,0 % in the considered period of the years 1998 until 2006.

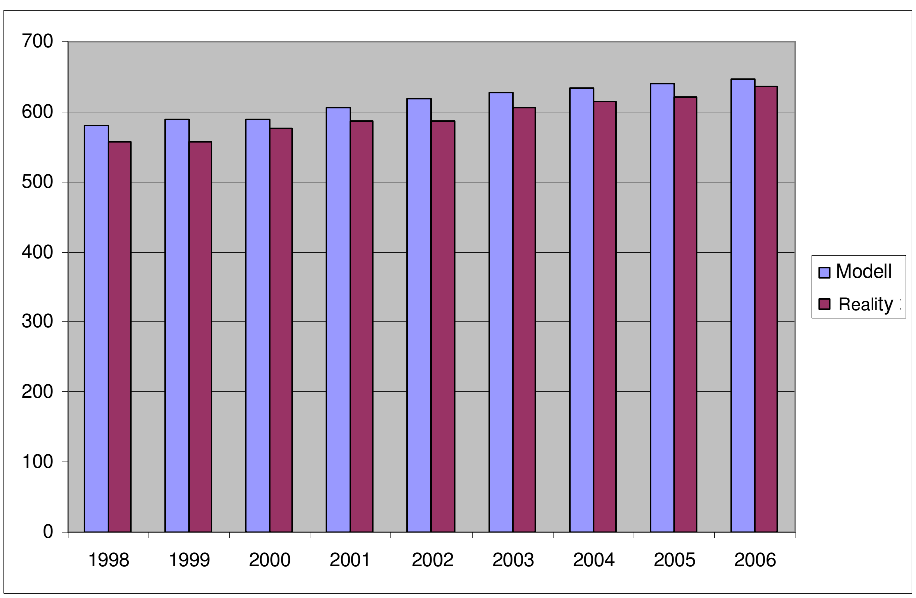

Figure 3: Produced quantities of electricity in the years 1998 - 2006

Model deviations from reality with respect to produced electricity are even smaller than for capacities. Values deviate between 1,7 % und 5,8 % in the years 1998 until 2006.

6 Model applications in enterprizes

At the current stage, the focus of the model development is on simulating the effects of environment related political decisions on the German electricity market. The main parameters of the market are short-term and average electricity price, amount of electricity production and production capacity as well as CO_2 emissions. The level of CO_2 taxes as well as feed-in tariffs for renewable energies is defined exogenously. They remain constant over the entire period of time, or are simulated as a proportionally similar increase of feed-in tariffs covering all renewable energies compared to the actual rates.

The model “Zertsim” was used for the first time in practice during a one-day workshop in Karlsruhe, in April 2008, organized by EIFER and the Chambers of Industry and Commerce of the region Rhein-Main-Neckar. The objective of the workshop was to show possible developments of the electricity sector of Germany under economic and environment related energy policy frame conditions. Under support of the model “Zertsim” various developments in form of future scenarios concerning electricity prices, production capacities on the basis of several energy sources as well as CO_2 emissions could be identified. Energy experts from utility companies and industry of the region defined the rates of input parameters (CO_2 tax, feed-in tariffs, extension of operation time of nuclear power plants and changes in demand) for the individual simulations and discussed the results directly afterwards.

The results of the eight scenarios, developed in the workshop are represented in the following section. Table 2 shows the essential input parameters developed by the corporate experts. The scenarios were compiled with the ambition to demonstrate separately the effects of economic and environment related policy variations on electricity prices and CO_2 emissions development. It is considered a time period between the years 1998 and 2026. In scenario 8, “Lifetime extension for nuclear power plants in Germany”, an extension of operation time of the plants is assumed for about 20 years for all nuclear power plants in Germany who are still in operation in the year 2009.

Table 2: Economic and environmental policy based scenarios in the time period 1998 until 2026

<table>
<tr><th>Item/ Scenario</th><th>Unit</th><th>Scen.1 Reference</th><th>Scen.2 Demand increase</th><th>Scen.3 Demand decrease</th><th>Scen.4 Fuel price high</th><th>Scen.5 Fuel price low</th><th>Scen.6 Policy high</th><th>Scen.7 Policy low</th><th>Scen.8 No nuclear phase out</th></tr>
<tr><td>Change of electricity demand</td><td>%/a</td><td>0</td><td>+1,5</td><td>-1</td><td colspan="2">0</td><td colspan="2">0</td><td>0</td></tr>
<tr><td>Price dev. (natural gas) 2005 – 2020</td><td>%</td><td>+50-60</td><td colspan="2">+50-60</td><td>+150</td><td>+30</td><td colspan="2">+50-60</td><td>+50-60</td></tr>
<tr><td>Price dev. (hard coal) 2005 – 2020</td><td>%</td><td>+100</td><td colspan="2">+100</td><td>+200</td><td>+50</td><td colspan="2">+100</td><td>+100</td></tr>
<tr><td>Feed-in tariffs 2000 – 2020</td><td>%</td><td>+/- 5</td><td colspan="2">+/- 5</td><td colspan="2">+/- 5</td><td>+ 50</td><td>- 30</td><td>+/- 5</td></tr>
<tr><td>Level of CO_2-tax from 2009</td><td>€/t. CO_2</td><td>40</td><td colspan="2">40</td><td colspan="2">40</td><td>100</td><td>20</td><td>40</td></tr>
<tr><td>Future nuclear power</td><td>-</td><td colspan="7">Nuclear phase out</td><td>No Nuclear phase out</td></tr>
<tr><td>Operation time extensions for all nuclear power stations</td><td>yrs.</td><td>0</td><td colspan="2">0</td><td colspan="2">0</td><td colspan="2">0</td><td>20</td></tr>
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The following two figures 4 and 5 show the development of the average electricity price of the eight scenarios.

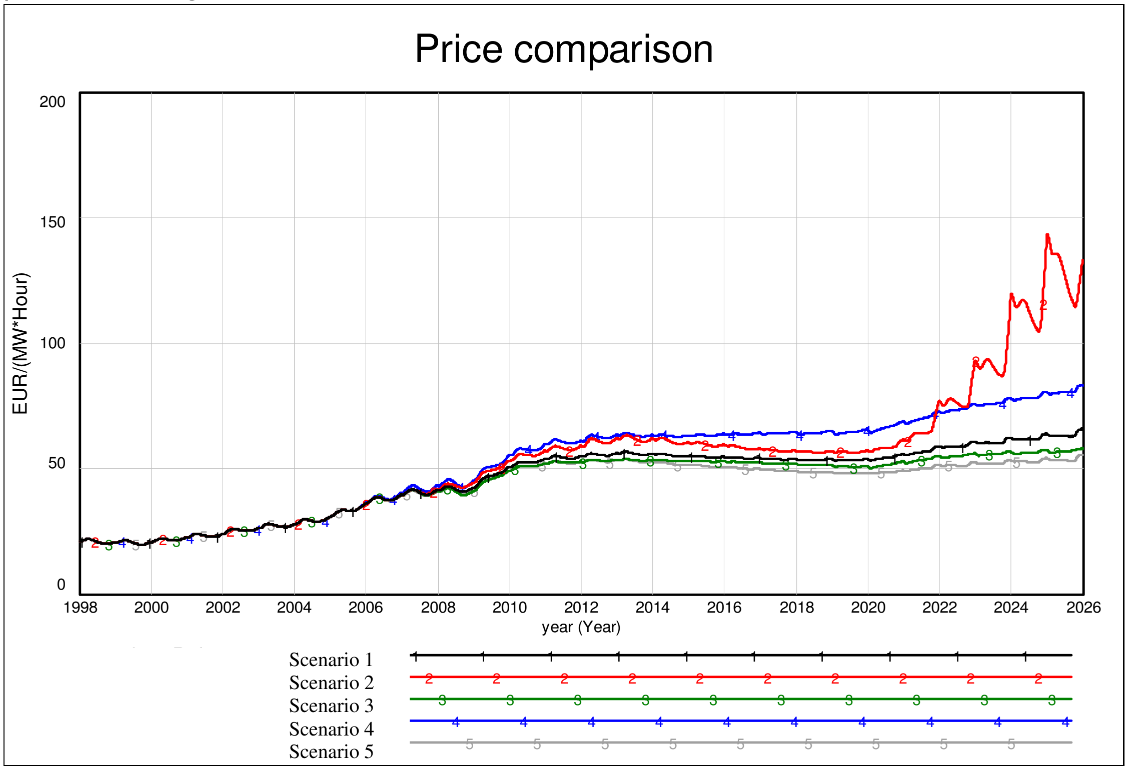

Figure 4: Comparison of the average prices of the scenarios 1-5

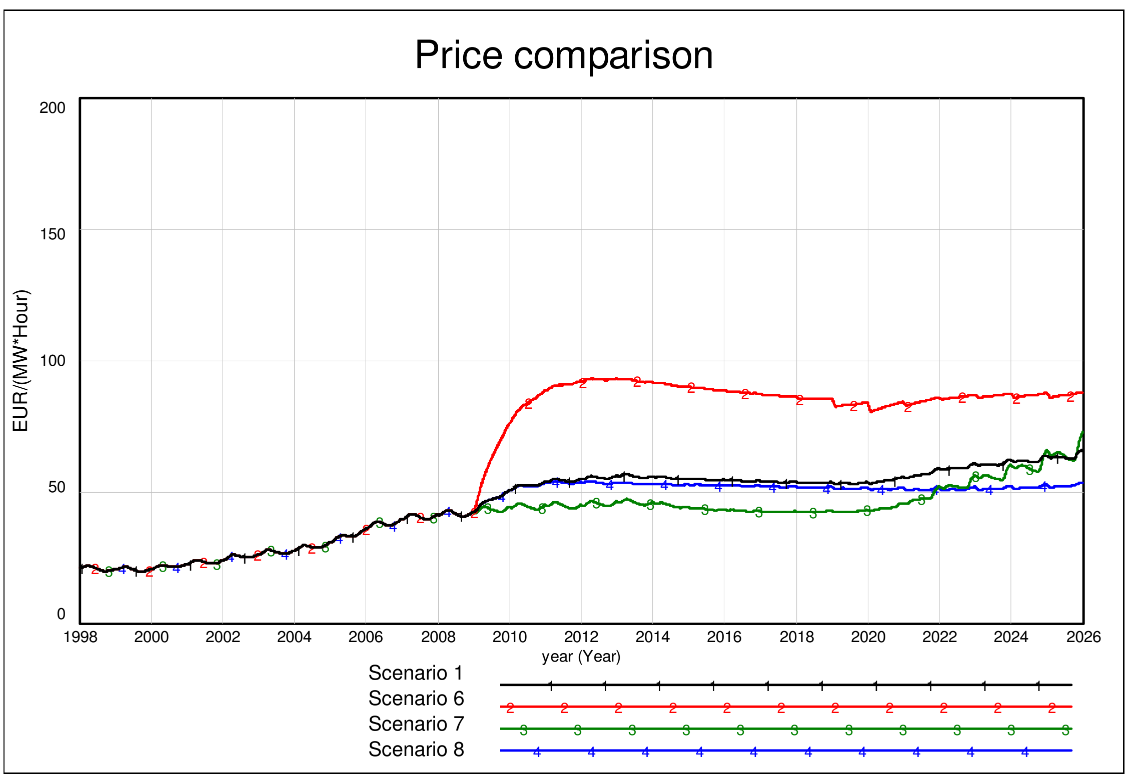

Figure 5: Comparison of the average prices of the scenarios 1, 6-8

It can be seen in scenario 6, that the introduction of a relatively high CO_2 tax (100€/ t CO_2) in 2009 and high feed-in tariffs for renewable energies – leads to the highest electricity price of 85€/kWh in the period from 2011 to 2023 (figure 5), compared to all other scenarios.

A price increase in scenario 2 is recorded from 60 €/ kWh in 2021 to 140€/ kWh in 2025 (figure 4). Reasons are the strong growth of demand for electricity and the phase out of nuclear power in Germany.

The lowest prices are obtained in those scenarios, where burdens from environmental policies were minimized (scenario 7). Moreover, if fuel prices remain on a relatively low level due to a stronger utilization of fossil fuelled power plants (scenario 5) or due to an operation time extension of nuclear power plants (scenario 8). With these actions it is possible to have a price cap for of 50 €/kWh.

Corresponding to those developments of CO_2 emissions of the eight scenarios could be seen in the following graphs.

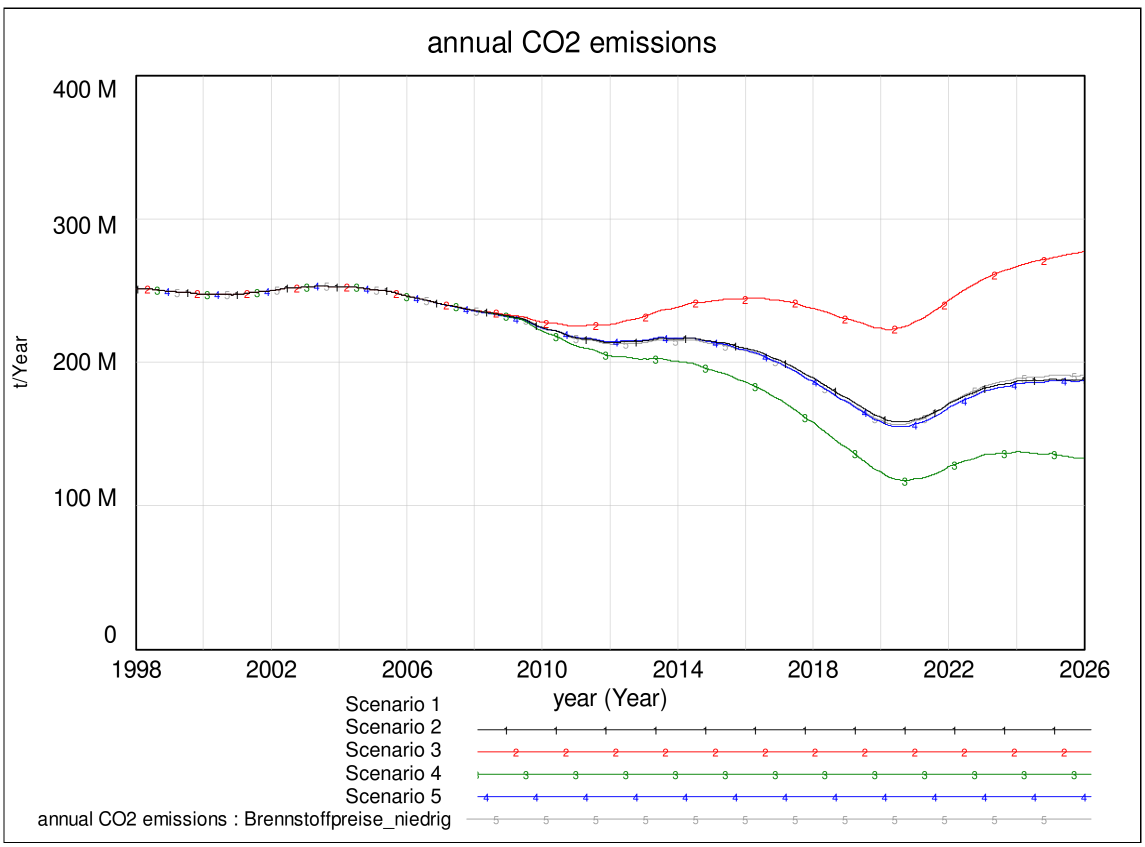

Figure 6: Comparison of CO_2 emissions in the scenarios 1–5

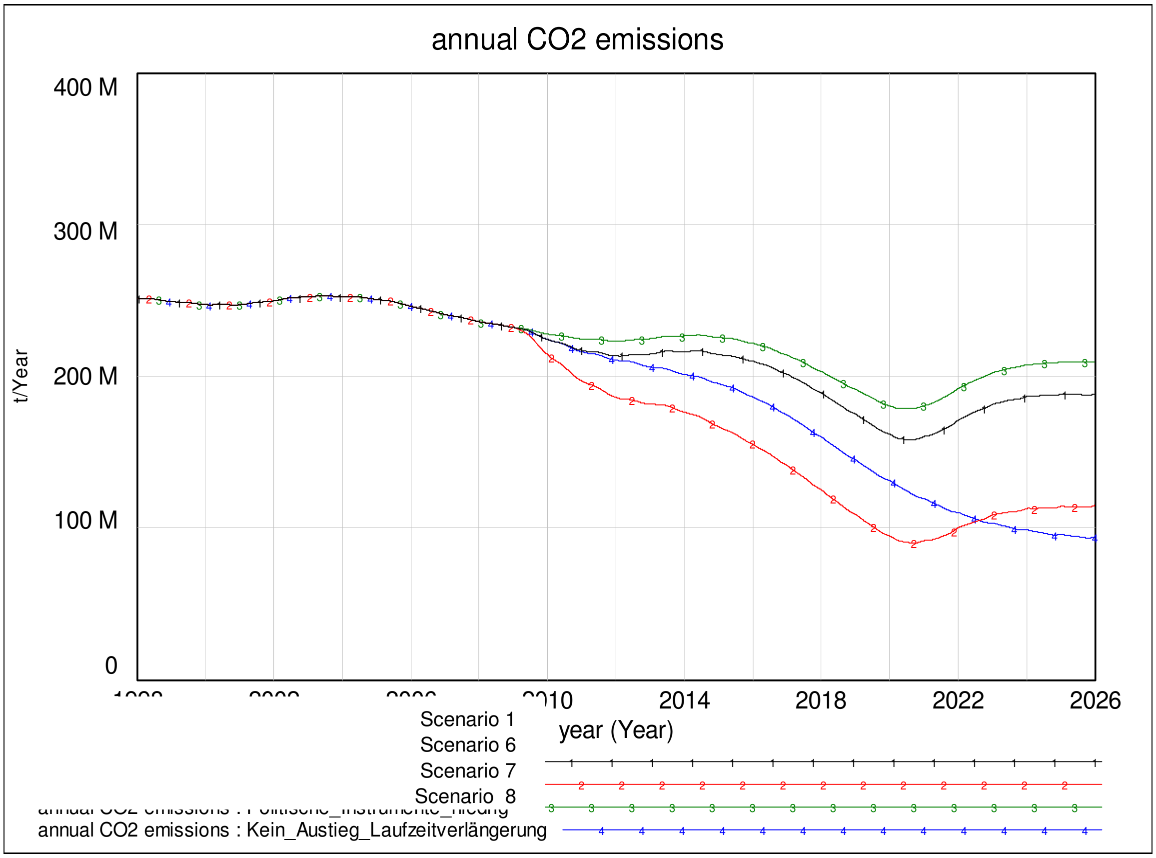

Figure 7: Comparison of CO_2 emissions in the scenarios 1, 6-8

The figures 6 and 7 show the largest effects for climate protection in scenario 6 by high environment related burdens from CO_2 taxes and high feed-in tariffs for renewable energies. With these policy instruments a reduction from 250 Mio. t CO_2 in the year 1998 to 90 Mio. t CO_2 in the year 2021 could be received. Furthermore, 155 Mio t/a CO_2 could be saved until the year 2026 according to 1998 by the extension of operational hours of nuclear power plants in Germany (scenario 8). A relatively high reduction of CO_2 emissions by 125 Mio t /a between 1998 and the year 2021 can be obtained by a decrease of electricity demand (scenario 3).

7 Results

The Implementation of environmental taxes and feed-in tariffs for renewable energies (scenario 6) leads to a strong increase in electricity prices from 45 €/MWh (2009) to 90 €/MWh (from 2013) and remains constant on that level until the end of the considered period. Similarly high fuel prices for gas und hard coal (scenario 4) causes relatively high electricity prices of 75 €/MWh (2025).

The prolongation of working hours of nuclear power plants in Germany (scenario 8) allows constant electricity prices on a relatively low level of (50 €/MWh) in the period 2010 to 2020. After the year 2020 a slight increase could be observed.

The largest reduction of CO_2 emissions occurs with the use of environmental policy instruments (scenario 6). It could be obtained a reduction from over 250 Mio. t/CO_2 (1998) to under 100 Mio. t/CO_2 (2023). The reduction results from the use of technologies for electricity reduction with low CO_2 emissions (Diminution of the share of conventional thermal power plants for the benefit of renewable energies).

An increasing demand for electricity by 1,5%/a results in the case of a nuclear phase out for Germany (scenario 2) to a price level of 140 €/MWh (2025), compared to 25 €/MWh (1998). This is the highest electricity price compared to all scenarios and an increase between 1998 and 2025 of 161%.

8 Conclusions and Outlook

The model „Zertsim" depicts complex causal relations based on the methodology of System Dynamics. It is able to show direct and indirect causalities between variables under use of short-, medium- and long-term causality loops.

After model calibration, which was time consuming, input parameter could be varied on demand. Results could be received already after one minute calculation time and the model output could be presented in a graphical manner.

With these features the model is in particular appropriate to provide support in workshops and events about the future development of the electricity sector.

With „Zertsim" temporarily disequilibria on the electricity market could be shown. With such a model more realistic price simulations with this respects are possible than with models which assume per definition market equilibria. An integration of market imperfections and strategic behaviour in system dynamic models are in principle possible.

From a comparison of the eight scenarios regarding the impacts on electricity prices and CO_2 emissions, it can be concluded:

The highest determining factors for high electricity price levels for the entire time horizon between 1998 and 2026 are: 1) Environment related policy instruments (High prices for CO_2 emissions, high feed-in tariffs), 2) fuel prices, 3) demand for electricity, and finally 4) extension of operation time for nuclear power stations in Germany.

Regarding CO_2 emissions the order of impacts with the highest CO_2 reduction is: 1) Environment related policy instruments, 2) extension of operation time for nuclear power stations in Germany, 3) demand for electricity and finally 4) fuel prices.

For improvements of the quality of model results, possible further developments as examples are shown:

Extension of the geographical scope of the model from a primarily German perspective to a Europe wide model.

Modelling of technology classes more in detail, in particular representing decentralized and renewable energies by different size classes and technology types.

Implementation of certificate markets for CO_2 emissions as well as for green and white certificates.

9 References

Forrester, J. W. (1961). Industrial Dynamics. MIT Press. Cambridge, Massachusetts, 1961

Vogstad, K.-O. (2004). A system dynamic analysis of the Nordic electricity market: The transition from fossil fuelled toward a renewable supply within a liberalised electricity market. Diss., Norwegian University of Science and Technology, Department of Electrical Power Engineering. Trondheim, 2004.