A system dynamics model for the German electricity market – model development and application

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Abstract:

The aim of this paper is to present impact studies of economic and environment related constraints on the German electricity spot market. The analysis was carried out using the system dynamics based model for the German electricity market, called "Zertsim". The model was applied for the first time in a workshop with entrepreneurs from the region of Karlsruhe in Germany. One result of the workshop was an order of factors impacting on the development of electricity prices and CO_2 *emissions. The most influential factors on high electricity prices are: 1) environmental constraints, 2) fuel prices, 3) electricity demand, and 4) extended operating time for nuclear power stations in Germany. Regarding* CO_2 *emissions, the highest impacts came from: 1) environmental constraints, 2) extended operating time for nuclear power, 3) electricity demand and finally 4) fuel prices.*

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1 Introduction

In the field of energy system analysis, different models can be used to analyze complex systems and provide appropriate and transparent decision support. Examples of such complex issues are the relations between climate change, market liberalization, globalization or energy and environmental policies and the energy system.

The aim of this paper is to present a study of the impact of economic and environment related constraints on the German electricity spot market. The analysis is carried out using a dynamic simulation model, which is based on the system dynamics methodology (Forrester 1961). This model type is seen as a complementary approach to other models like linear programming (e.g. MARKAL, Fishbone et al. 1983, Loulou et al. 2004, TIMES, Loulou et al. 2005), static simulations (e.g. Rebus, Voogt et al. 2001) or general equilibrium models (e.g. GEM-E3, Kouvaritakis et al. 2002) supporting decisions for strategic planning in the energy sector.

In the first part of the paper, the dynamic simulation model "Zertsim" for the German electricity market will be described. In particular the properties of the model will be discussed and there will be a short description of the model parts. To illustrate the results of the model in the second part of this paper, a first application in a workshop will be provided, showing potential developments of the electricity market in Germany.

2 The « Zertsim » model

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

The objective of the "Zertsim" simulation model is in particular the analysis of short and long-term price reactions (spot market price and the annual average price) to the electricity market, as a consequence of different energy and environmental policies. In an initial step, EIFER developed the dynamic simulation model, "Zertsim", based on the system dynamics theory, for the analysis of the electricity market in Germany. It covers a period extending from 1998 until 2026. The model is based on the PhD thesis of K. Vogstad, who developed a comparable model for the electricity market of the Nordic countries (Vogstad 2004).

The current version of "Zertsim" enables short time calculations of approximately one minute. Due to the variation of input parameters and immediate presentation of results, the model supports discussions regarding the future of electricity markets in workshops and conferences. In addition, the model is suitable to provide decision support for investments in decentralized and renewable energies.

"Zertsim" was implemented with using Vensim software, which provides graphic support for programming as well as for presenting results.

3 Model properties

The following table presents specific model properties of the “Zertsim“.dynamic simulation model

Table 1: Overview of the properties of the “Zertsim” model

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 resource availability	Partially endogenous
Multi-periodic/ time horizon	In annual steps, 1998 - 2025
Geographical scope	National, Germany, (one international connection to the other European countries as one bloc)
Environment related policy instruments	CO_2 tax, feed-in tariffs, optional: Nuclear phase out
Demand side	Aggregation of load curve, no distinction of economic sectors (like industry, tertiary, transport etc.)
Behavior of market actors	No distinction between individual actors with individual behavioural functions

3.1 Model characterisation

In the “Zertsim” model, the German electricity market is modelled with 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 of a causality loop is the implementation of a 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 of electricity affect each other in terms of short-term behaviour, while learning curves and resource availability affect electricity prices on a medium- or long-term basis.

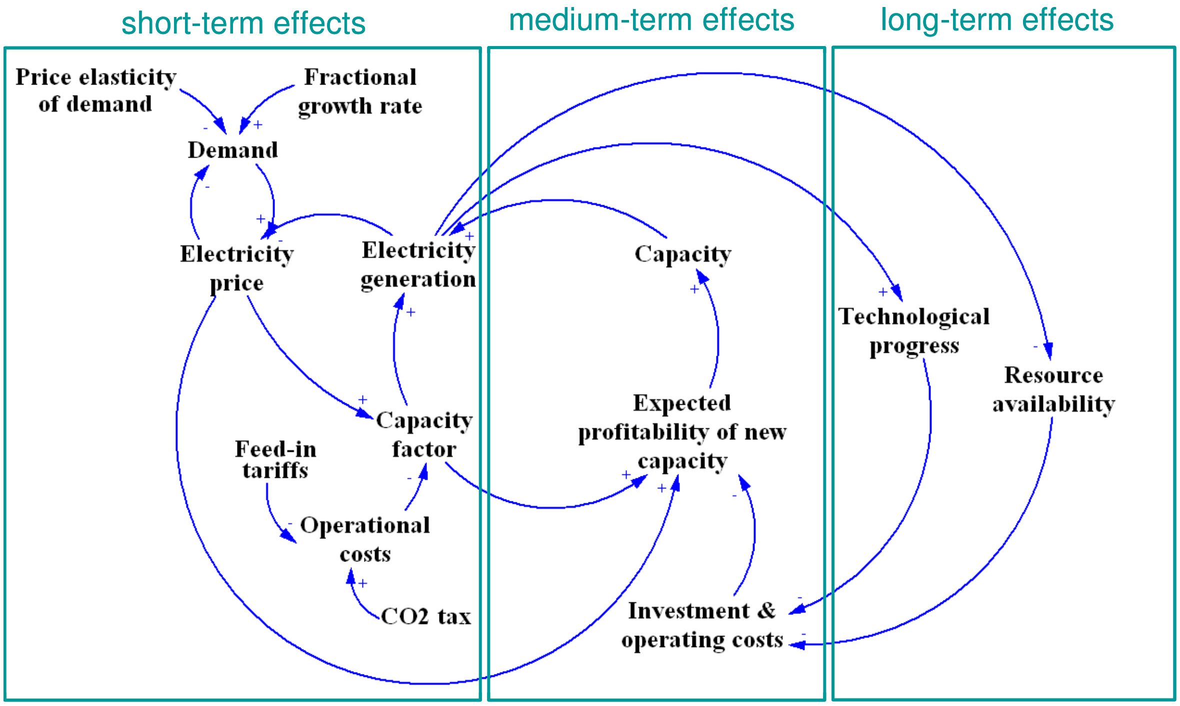

Figure 1: ”Causal loop diagram“, core model of „Zertsim“ (adapted from Vogstad, 2004)

The dynamic mechanism of the model enables 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 as in Linear Programming (LP-) models.

Due to 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 period considered is determined by the initial value and the investment decisions referring to a period of profitability expectations of 5 years. Therefore, the capacities of each technology for electricity production for example are the result of their development over time and they are not necessarily optimal in relation to costs.

3.2 “Zertsim”, a One-Sector model

The model concentrates on the economic sector of the electricity generation and unlike general equilibrium models it does not consider other economic sectors (like public or domestic sector) or all industrial branches of a country. The model can currently be used for the exclusive analysis of the electricity sector without analysing macroeconomic impacts across various economic sectors. Moreover it is possible in principle to integrate a heat market in the model, but it is not presently the case.

3.3 Descriptive approach

The descriptive character of “Zertsim” signifies the missing objective function. Rather it shows the impact of variables on others, without following a normative objective function. For example, cost minimization of energy systems occurs in prescriptive models.

3.4 Techno-economic model

An outstanding feature of the model besides its descriptive character, is the description of technologies via technological, economic and environment related parameters (techno-economic model). In the model, parameters of power plants are described for the supply side of the electricity market on an aggregated level, of technology classes of energy carriers and/or transformation technologies (uranium, crude oil, natural gas, natural gas CCS, natural gas peak load turbines, hard coal, hard coal CCS, lignite, hydro power, biomass, biogas, wind onshore, wind offshore, photovoltaic).

Various technological factors and the principle of function (e.g. Carnot- or Rankine cycle combustion engine etc., gas turbine) are not considered in the present model. Each technology differs in terms of investment, operating costs, CO_2 emissions, resource potential and in its potential of technological progress.

Table 2 shows the most important input and output parameters.

Table 2: Main input- und output parameters

INPUT	OUTPUT
• Electricity demand • Fuel prices • Investment and variable costs • Feed-in tariffs, CO_2 tax • Capacities and operational time of nuclear power stations	• Electricity price (spot price and average price) • Production capacities per energy carrier • Produced quantities of electricity per energy carrier • CO_2 emissions

3.5 Technological progress and resource availability

The main parts of the model which relate to long-term impacts on the energy system are technological progress and resource availability. They are partially endogenously modelled by learning curves. This is important for the evaluation of policies which stimulate the use of new generation technologies.

3.6 A “Bottom-up” model approach

Like most other simulation models, “Zertsim” is based on a bottom-up approach. In a bottom-up approach the technologies for electricity production are specified individually, unlike top-down models with a highly aggregated level for the technologies. In top-down models the technologies are described by production functions, e.g. in general equilibrium models.

3.7 Multi-periodic time horizon

The time horizon of the model is the year 2026 for analyzing EU policies with the model whose target values refer to the year 2020. Concerning the level of analysis, “Zertsim” is able to display annual changes of the output parameters over the entire model period from 1998 to 2026.Thereby, changes in demand and fluctuating energies are modelled on a weekly level for the entire year. Alternatively, it would also be possible to integrate different time slots on a daily, monthly or seasonal basis.

3.8 Geographical scope

The model considers Germany as a liberalized electricity market. Regarding the international transmission grid, exchanges between Germany and the other countries of continental Europe are modelled as total volume per year. The volume is restricted and remains constant for reasons of simplificity. Electricity transmission lines between each of the European states will not be described, as well as the internal grid of Germany. Concerning electricity price development it is assumed that there is no influence from transmission capacity. It means there is a sufficient transmission capacity within Germany even with increasing electricity production. Furthermore there is no differentiation between utilities and private households as electricity producers. However, a model extension for more European and Non-European countries is possible.

3.9 Environment related policy instruments

With the model focus on Germany, policy instruments such as feed-in tariffs for renewable energies as well as CO_2 tax are currently implemented. Feed-in tariffs are integrated because they are considered an important support for the promotion of renewable energies. Moreover a CO_2 tax was introduced into the model from the year 2009 onwards in order to study the impacts of emission constraints like the EU CO_2 emission trading system in a first approach.

Finally the model offers the choice between the simulation of nuclear power phase out in Germany and the extension of the operating time of these power plants.

3.10 Demand for electricity

The demand side is indicated as an aggregated load curve. There is no distinction between various economic sectors (industry, residential, tertiary, transport, agriculture) or industrial branches. But this is in principle possible.

3.11 Behaviour of market players

In the model a limited rational behaviour among market players is assumed when regarding their investments in electricity generation capacity. Furthermore, time delays in the availability of new capacities will be considered. This happens by modelling the time needed for the application processes to public authorities and the construction of new generation facilities. The time frames vary between each energy source and technology. In addition, the role of expectation formation will be explicitly recorded in the model. But an individual (different) behavioural function of the market participants, provided in a multi-agent approach, is not integrated in “Zertsim”. Though, it is in principle possible in a model based on system dynamics.

Besides its model properties, “Zertsim” could be described by its main feedback loops and the structure of the model (Sub modules). That will be covered in the next chapter.

4 Main feedback loops

The modelling of causal loops is a significant indicator for simulation models following the system dynamics approach. Referring to Vogstad (2004), “Zertsim” consists of 5 major loops presented in the table below.

Table 3: Major loops in the “Zertsim” model

- Demand loop
- Capacity acquisition loop
- Generation scheduling loop
- Technological progress loop
- Resource depletion

The “demand loop” is the most important loop in terms of price behaviour on the electricity market as a core component of the model. The electricity demand reacts in response to changes in electricity prices. High electricity prices reduce demand for electricity while high demand reduces electricity prices.

As a balancing loop for the “demand loop”, a “capacity acquisition loop” is integrated in the model on the supply side. This loop describes the application processes for building plants as well as their investments and the construction of new production capacities.

Moreover, the supply site is determined by the “Generation scheduling loop”. Using this loop, the utilization of the different capacities for every class of technology is coordinated as a function of the electricity price.

Another important interaction of variables is the loop which determines the “technological progress”. It expresses the cost degression due to the accumulation of experience resulting from a capacity increase in each technology class. Technological progress affects costs on a long-term basis and consequently the capacity extension of each technology class. Regarding the investments, technological progress is modelled partially as endogenous related to investment and totally exogenous in terms of efficiency improvements.

Finally, the loop of “resource depletion” regulates the depletion of remaining available resources. In this model, the resource availability is outlined as exogenous with an assumed unlimited supply of fossil resources.

5 Model components

The major loops have been presented as the core of the model. In the following chapter, the model structure will be described by sub modules referring to the loops. As indicated in table 4, the “Zertsim” model displays the German electricity market and its development by eleven main sub-modules.

Table 4: Main sub’modules of “Zertsim”

- Electricity market price
- Generation Scheduling
- Demand
- Exchange
- Profitability assessment
- Capacity acquisition
- Capacity vintage
- Resource efficiency
- Technological progress
- Resource availability
- CO_2 emissions

The eleven main sub-modules are presented briefly in the following table:

Table 5: Description of the eleven sub-modules of “Zertsim”

Name of sub-module	Function
Electricity Market Price	Dynamic formulation of price formation in the spot market. An approximate representation of the future / forward price is made as an adaptive exponential smoothed forecast of the yearly average price.
Demand	Representation of the electricity demand with a yearly fractional growth, a price elasticity of demand and a daily variation profile.
Generation Scheduling	Coordination of the capacity utilisation for each technology type according to the price
Exchange	Representation of the aggregated exchange with the European countries, which are represented as one bloc.
Profitability Assessment	Calculations of the expected profitability of new investments based on available information on prices and costs. The profitability is based on the net present value criteria, using a return on investment index.
Capacity Acquisition	Description of the process of applying for permits before investing and building new capacities.

Name of sub-module	Function
Capacity Vintage	Representation of the capacity vintage structure consisting of three vintages
Resource Efficiency	Keeps track of the age dependent attribute "efficiency" for each technology and vintage. Efficiency has a strong impact on operating costs and thus the capacity utilizations.
Technological Progress	Description of the cost reductions taking place as experience cumulates. Technological progress is partly exogenous for investments and entirely exogenous for improvements in efficiency
Resource Availability	Pictures the remaining available resources for development. Resource availability is also partly exogenous, i.e. no constraints on fossil and nuclear fuels
CO_2 Emissions	Gives information on the development of technology-specific and the total CO_2 emissions resulting from electricity production. A CO_2 tax and feed-in tariffs are incorporated.

(adapted from Vogstad, 2004)

6 Model validation

A first validation of the model “Zertsim” was done by comparisons to statistical data from the European Energy Exchange (EEX) and the German and Federal Ministry of Economy (BMWI) with regard to “electricity spot prices” and the “installed capacities” (Figures 2 and 3).

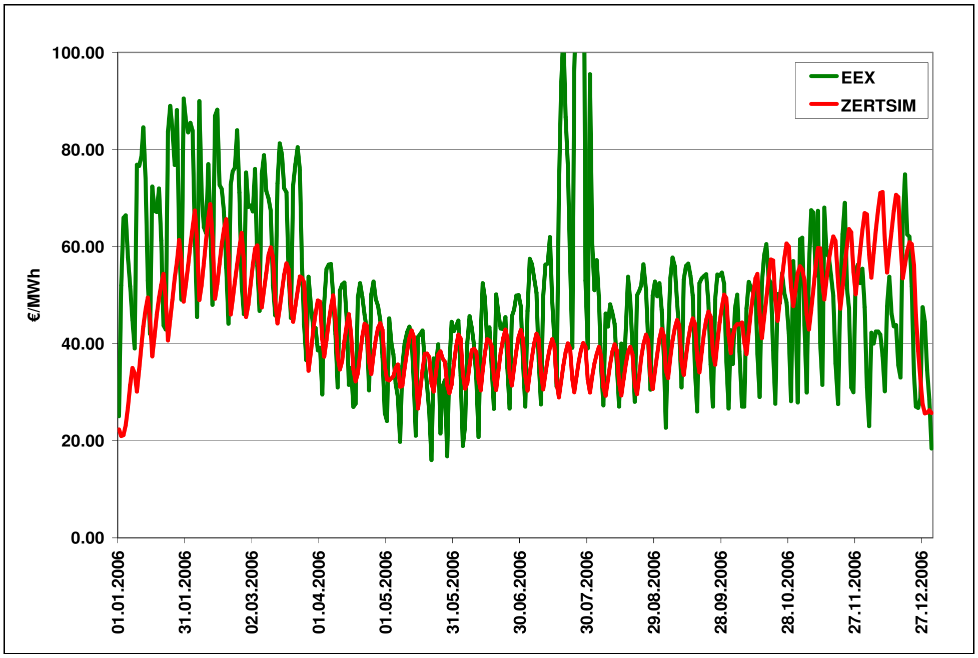

Figure 2: Electricity “spot” prices of the year 2006

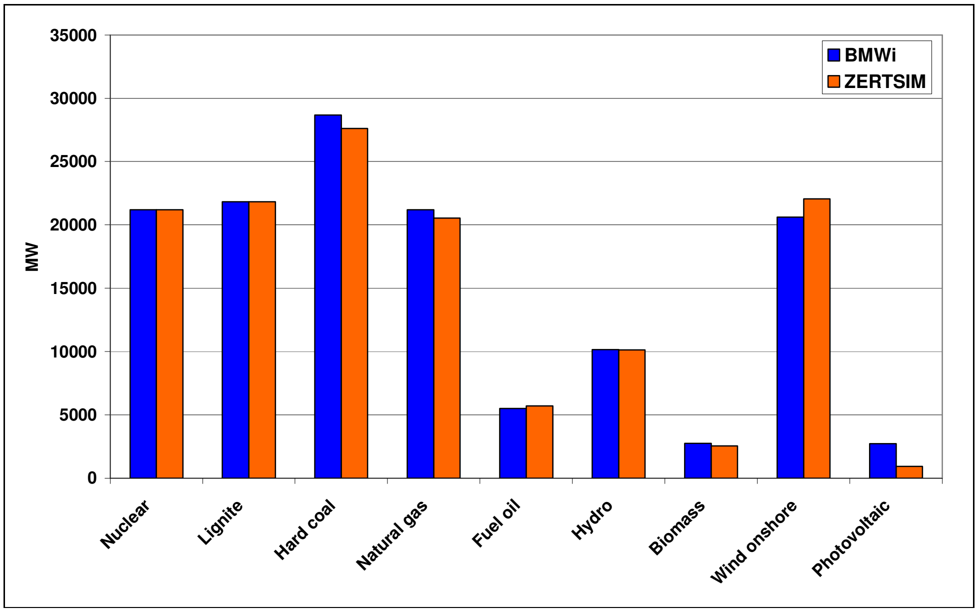

Figure 3: Installed capacities for electricity generation in Germany in the year 2006

Installed capacities for electricity generation in Germany in the model deviate from statistics between -3,98 % (biomass) and 7,9 % (wind onshore) in the year 2006.

7 Model applications in businesses

Currently, 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 (‘spot’) and average electricity price”, “amount of electricity produced” 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 current 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 Rhine-Main-Neckar region. The objective of the workshop was to show possible developments of the German electricity sector under economic and environment related energy policy frame conditions. With support from the “Zertsim” model, various developments could be identified in the form of future scenarios concerning electricity prices, production capacities on the basis of several energy sources as well as CO_2 emissions. 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 various simulations and discussed the results directly afterwards.

The results of the eight scenarios, developed in the workshop are represented in the following section. Table 6 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 the development of CO_2 emissions. A period between the years 1998 and 2026 is considered. In scenario 8, “No nuclear phase out for nuclear power plants in Germany”, an extension of about 20 years of the operation time is assumed for all nuclear power plants in Germany which are still in operation in the year 2009.

Table 6: Economic and environmental policy based scenarios in the period 1998 to 2026

Item/ Scenario	Unit	Scen.1 Reference	Scen.2 Demand increase	Scen.3 Demand decrease	Scen.4 Fuel price high	Scen.5 Fuel price low	Scen.6 Policy high	Scen.7 Policy low	Scen.8 No nuclear phase out
Change in electricity demand	%/a	0	+1,5	-1	0		0		0
Price develop. (natural gas) 2005 – 2020	%	+50-60	+50-60		+150	+30	+50-60		+50-60
Price develop. (hard coal) 2005 – 2020	%	+100	+100		+200	+50	+100		+100
Feed-in tariffs 2000 – 2020	%	+/- 5	+/- 5		+/- 5		+ 50	- 30	+/- 5
Level of CO_2-tax from 2009	€/t. CO_2	40	40		40		100	20	40
Future nuclear power	-	nuclear phase out							no nuclear phase out
Extension of operation time of all nuclear power stations	yrs.	0	0		0		0		20

The following two figures 4 and 5 show the development of the average electricity price for the eight scenarios.

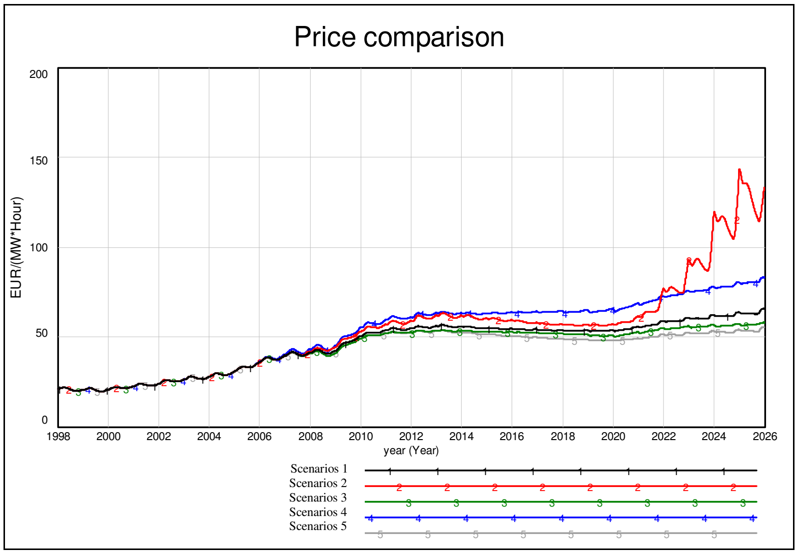

Figure 4: Comparison of the average prices for scenarios 1-5

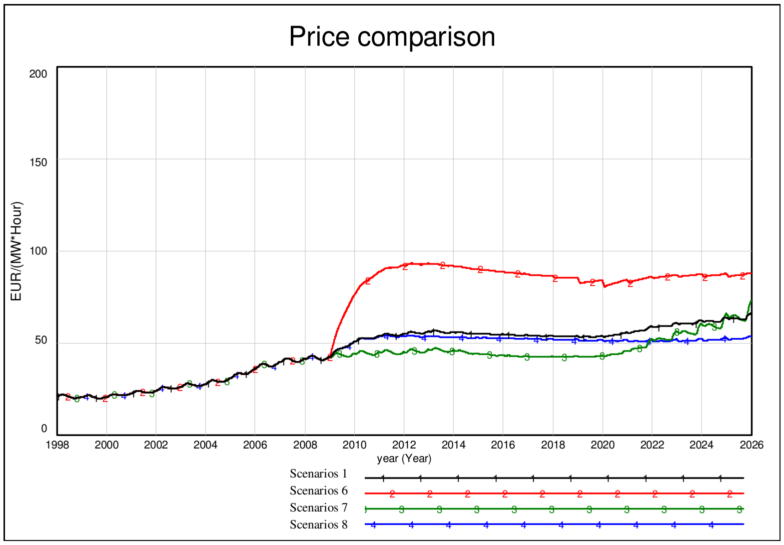

Figure 5: Comparison of the average prices for scenarios 1, 6-8

In scenario 6 (figure 5), it can be seen 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 is recorded in scenario 2 from 60 €/ kWh in the year 2021 to 140€/ kWh in the year 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, low prices could be found, 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 extension of nuclear power plant operating time in Germany (scenario 8). With these actions it is possible to have a price of about 50 €/kWh.

Corresponding to these developments CO_2 emissions for the eight scenarios could be seen in the following figures 6 and 7.

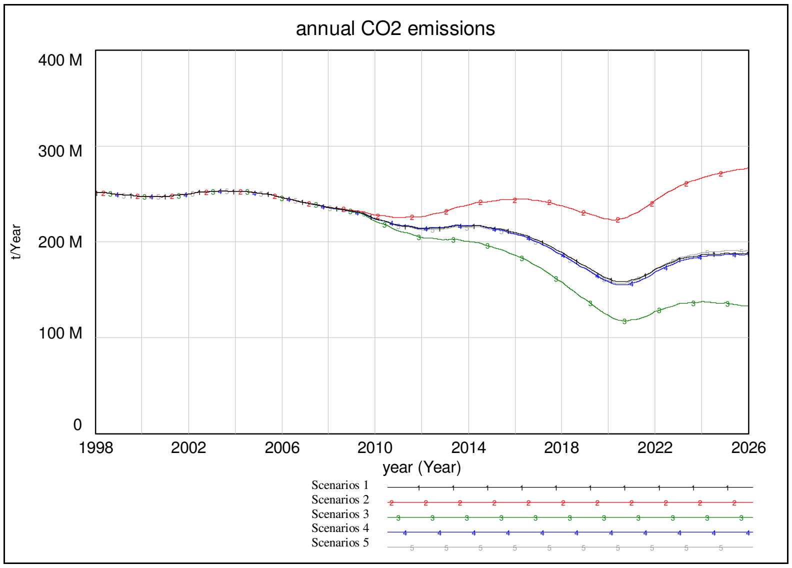

Figure 6: Comparison of CO_2 emissions in the scenarios 1–5

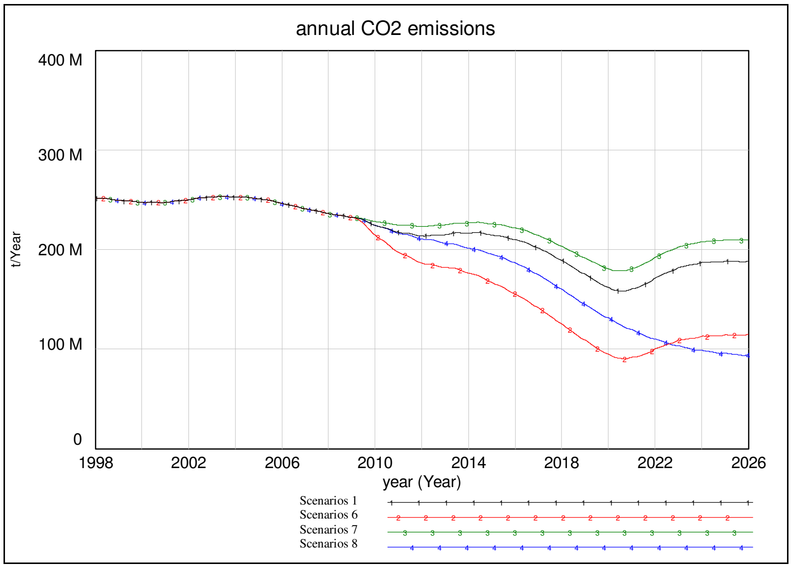

Figure 7: Comparison of CO_2 emissions in the scenarios 1, 6-8

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

9 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 (2013) and remains constant at that level until the end of the period considered. Similarly, high fuel prices for gas und hard coal (scenario 4) cause relatively high electricity prices at 75 €/MWh (2025).

The prolongation of nuclear power plant operation in Germany (scenario 8) allows constant electricity prices at the relatively low level of (50€/MWh) in the period 2010 to 2020. After the year 2020 a slight increase can be observed.

The largest decrease in CO_2 emissions occurs with the use of environmental policy instruments (scenario 6). There is a reduction from over 250 Mio. t/CO_2 (1998) to under 100 Mio. t/CO_2 (2023). The reason is the use of technologies with low CO_2 emissions for the production of electricity (decrease in the share of conventional thermal power plants for the benefit of renewable energies).

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

10 Conclusions and outlook

The paper describes the composition and functionality of the system dynamics based “Zertsim“model, which was developed by the European Institute for Energy Research (EIFER). This model shows the German electricity market. This model is based on a similar model for the Nordic electricity market (Vogstad 2004), which was transferred, adapted and calibrated for German conditions.

Due to the use of the system dynamics method, the “Zertsim” model enables the depiction of direct and indirect causalities between parameters with the aid of short-, medium- and long-term feedback loops.

In the “Zertsim“ model, impact variables for supply and demand could be varied and the effects can be presented immediately in a graphical manner as model results. With such features, the model is particularly appropriate for workshops and conferences while discussing possible future developments of the electricity sector for providing rational support in the opinion building processes.

A first application of the model was used in a workshop held in Karlsruhe, Germany which gathered experts from utilities and from the energy intensive industries of the Rhine-Main-Neckar region. They formulated eight scenarios for the future development of the German electricity market supported by the “Zertsim” model with the intention of finding a priority for the major impact factors for the electricity market development under certain economic and environment related frame conditions.

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

The order of determining factors for high electricity prices, for the entire time horizon between 1998 and 2026 under the assumptions made, is:

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 operating time for nuclear power stations in Germany.

Regarding CO_2 emissions, the order of the determining factors for the highest CO_2 reduction is:

1) Environment related policy instruments,

2) Extension of operating time for nuclear power stations in Germany,

3) Demand for electricity and, finally

4) Fuel prices.

Further model validation and improvements as well as additional model extensions are the next steps. Model enlargements are seen in a higher level of detail for technology classes to distinguish de-/centralized as well as conventional/ renewable electricity generation technologies, the integration of neighboring countries on a detailed level as well as the elaboration of the demand side by economic sectors. Not at least the inclusion of certificate markets (CO_2-, green and white certificates) as major parts of environmental policies are planned.

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