On the Impact of CO_2 Emission-Trading on Power Generation Emissions

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Abstract

Under the Kyoto Protocol, governments agreed on and accepted CO_2 reduction targets in order to counter climate change. In Europe one of the main policy instruments to meet these reduction targets is CO_2 emission-trading (CET), which was implemented as of January 2005. In this system, companies active in specific sectors must be in the possession of CO_2 emission rights that equals the amount of CO_2 emitted. Any surplus can be sold; any deficit must be compensated for by acquiring rights. Effectively, by pricing of CO_2 emission the external effects are partly internalized to the economy. By limiting the total amount of rights – the cap – the EU and its Members States must make sure a suitable price of rights is formed and trade amongst the parties involved emerges. The magnitude of the CO_2 cap determines the scarcity of rights. A major argument to introduce tradable emission rights, instead of, for instance, taxes, has been that "the invisible hand" of the market would lead to emission reduction by those who can achieve reduction at the lowest cost.
In Europe, electricity generation accounts for one-third of CO_2 emissions; in the Netherlands this is more than 50% of the sectors under CET. Its success therefore depends on the emission reduction by power generation. This sector, however, has been liberalized, reregulated and privatized in the last decade. Today power generation is separated from transport and supply. Around Europe, autonomous companies decide on (dis)investment in power generation facilities.

Simulations over an extensive scenario-space show that there is an impact of CO_2 emission-trading. Portfolio shift is observed to be different by the implementation of CET (see Figure 1). However, the effect is relatively small and late: absolute emissions by power generation rise under most scenarios. This corresponds to the dominant part of current capacity expansions plans in the Netherlands (46-52%) and Germany (68%) that are to build coal based power plants, the most CO_2 intensive option available. It seems surprising that even after the introduction of CET current power generation capacity expansion plans indicate a preference for coal. Apparently the economic effect of CO_2 emission-trading is not sufficient to outweigh the incentives to choose for coal.

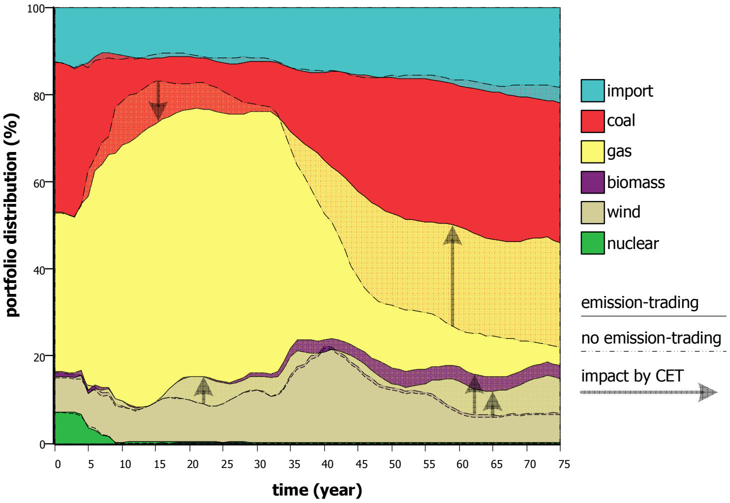

Figure 1. The average impact of CO_2 emission-trading on the portfolio

Keywords: Agent Based Model, Emission-Trading, Power Production.

Introduction

Under the Kyoto Protocol, governments agreed on and accepted CO_2 reduction targets in order to counter climate change (UNFCCC 1998). In Europe one of the main policy instruments to meet these reduction targets is CO_2 emission-trading (CET), which was implemented as of January 2005 (Directive 2003/87/EG; Europese Unie 2004). In this system, companies active in specific sectors must be in the possession of CO_2 emission rights that equals the amount of CO_2 emitted (EnergieNed 2006). Any surplus can be sold; any deficit must be compensated for by acquiring rights. Effectively, by economic pricing of CO_2 emission the external effects are partly internalized to the economy. By limiting the total amount of rights – the cap – the EU and its Members States must make sure a suitable price of rights is formed and trade amongst the parties involved emerges. The magnitude of the CO_2 cap determines the scarcity of rights. A major argument to introduce tradable emission rights, instead of, for instance, taxes, has been that "the invisible hand" of the market would lead to emission reduction by those who can achieve reduction at the lowest cost (Smith 1776; Svendsen 1999; Ehrhart *et al.* 2003; Svendsen & Vesterdal 2003).

In Europe, electricity generation accounts for one-third of CO_2 emissions; in the Netherlands this is more than 50% of the sectors under CET (Cozijnsen 2005). Its success therefore depends on the emission reduction by power generation. This sector, however, has been liberalized, reregulated and privatized in the last decade. Today power generation is separated from transport and supply. Around Europe, autonomous companies decide on (dis)investment in power generation facilities.

The central question in this paper is:

What long-term impact of CO_2 emission-trading on CO_2 emissions can be expected in electric power generation?

In this paper, the effect of CET on the emissions in electric power generation is quantified with an agent-based model. The paper is structured as follows. First, the background is presented as well as some notions on the perspective used in this paper. Next, the developed model is presented, including some remarks on its implementation. Consecutively, an analysis of the simulation results is presented. Finally, conclusions are drawn.

Background and perspective

The electricity sector has been liberalized in the last decade, unbundling power generation, transport and supply. Consecutively, the EU implemented an emission-trading scheme, by which electricity generating companies are obliged to have emission right to cover their emission.

A socio-technical systems-perspective is adopted to analyze this system (Ottens *et al.* 2006). In this perspective, the technical system of electricity generation and emission-trading is distinguished from the social system. The technical subsystem contains physical apparatus, such as power generation facilities, electricity grids and consumer equipment, and laws of physics apply to this subsystem. The social subsystem contains actors, engaging in contracts with each other and owning and operating components of the physical subsystem, under social laws such as regulatory regimes. In Figure 2 an overview is given of the electricity generation system, including emission-trading, from a socio-technical perspective.

A limited number of companies are active in (large-scale) electric power generation: a tight oligopoly is in place (Vries 2004). In the Netherlands, mainly facilities are in place using natural gas and coal. To a lesser extent other sources are used, such as nuclear, wind and biomass (EnergieNed 2006). In Table 1, the main characteristics of the energy sources are stated.

CO_2 emissions are energy source dependent: coal is the most CO_2 intensive; gas is less CO_2 intensive and nuclear and wind CO_2-free. Also biomass is counted as carbon-free, since only short-cycle carbon is used: the carbon uptake of the biomass chain equals the carbon emission and can therefore be ignored. Contrary to the carbon-intensity, the coal is a relatively cheap fuel compared to natural gas. Uranium can be acquired at even lower cost, if compared on an energy basis.

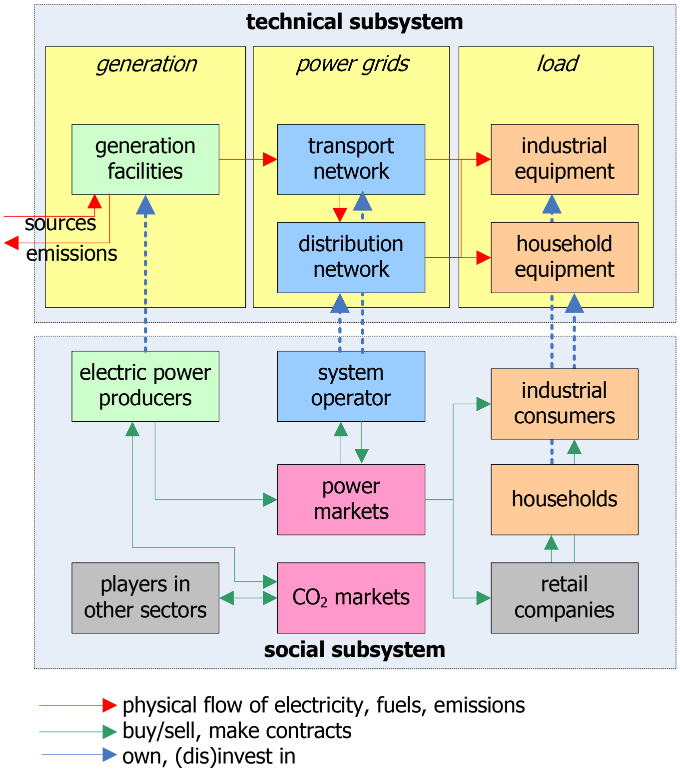

Figure 2. Socio-technical system of electricity production and emission trading

Electricity is transported through a high voltage transport grid, owned and controlled by system operators. Medium voltage distribution grids are used locally. Households buy electricity from retail companies that are active on power markets in order to buy the contracted electricity. Some large industrial consumers buy their electricity on the market themselves. The main power market in the Netherlands is the bilateral market, on which 80% of the electricity is sold. The rest is sold on the spot market.

Although many incremental innovations drive-down the CO_2 intensity of electricity generation (in Mton CO_2 per kWh electricity produced), a total reduction of emission from the sector is hard to achieve. The demand for electricity has been rising 2% per year on average for the last decades, with increase in population and increase in energy-intensity of living standards as main reasons. Whilst the demand for electricity is relatively inelastic to changes in the price, the CO_2 intensity of electricity generation should decline significantly for an absolute decrease in emissions on the mid-long term. It may be seen therefore it is not implicit that through CET the sector's CO_2 emission would reduce dramatically.

The impact of CET on consumers is by affecting the bid prices of electricity suppliers. This impact is twofold. First, an increase in electricity prices leads to a decrease in demand. Since – especially on short

Table 1. Characteristics of energy sources.

energy source	*availability*	*energy density*	*carbon-intensity*	*fuel costs*	*adoption*
natural gas	decreasing	low	low	very high	47%
coal	high	high	high	low	45%
uranium	high	very high	none	very low	2%
wind	uncertain	n/a	none	none	5%
biomass	increasing	medium	short-cycle	medium	1%

term – demand is inelastic to price, this effect is little. Second, the attractiveness of suppliers shifts towards less CO_2 intensive electricity producers: since emissions are priced, CO_2 intensive producers are more expensive and therefore a less attractive supplier for consumers. Consequently, this impact does not lead to a decrease in demand.

Because the operational flexibility of power plants is limited, CO_2 intensity of currently operating equipment cannot be decreased significant. Therefore, significant CO_2 reductions can be achieved in two ways:

- by a shift in the electric power generation portfolio (for instance by replacing coal based power plants by the use of natural gas, or by the diffusion of biomass power plants, replacing coal and/or natural gas based power plants);
- by innovative technologies that have lower costs operational *and* lower CO_2 intensive power generation.

Although CET can increase the incentive to innovate, the development programs of those technologies are not directly influenced by CET. Consequently, the main impact of CET is on *investment decisions* by electricity producers and this paper focuses on that impact (see also Figure 3).

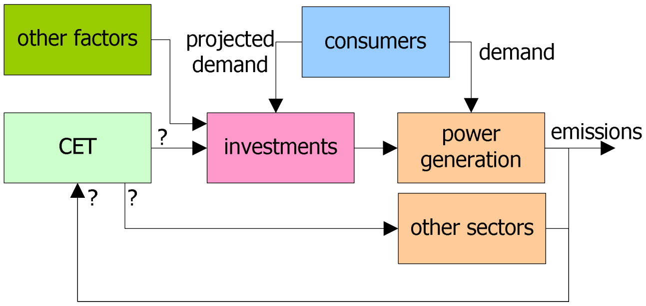

Figure 3. The effect of CET on electricity generation

Model development

To elucidate the impact of CET on the power generation sector's CO_2 emission an agent-based model (ABM) was built. An agent-based simulation model may be defined as "a collection of heterogeneous, intelligent, and interacting agents, which operate and exist in an environment, which in turn is made up of agents" (Epstein & Axtell 1996; Axelrod 1997). An ABM thus is a set of interacting '*agents*' with certain properties. An agent is defined as "an agent is an encapsulated computer system that is situated in some environment and that is capable of flexible, autonomous action in that environment in order to meet its design objectives" (Jennings 2000). Although in the literature different sets of properties for agents are proposed (Bussmann *et al.* 1998; Weiss 2000), of which the core components are:

- a set of goals;
- a working memory;
- a social memory;
- a set of rules of social engagement.

Agents have goals and can take actions to reach those goals. The set of goals, are objectives of the agent that it *wants* to accomplish. The working memory of an agent is a set of information about itself, called the *state*. The social memory is a set of knowledge on the behaviour of the agent and other agents. Past actions and interactions build this memory. Social engagement rules define the social behaviour of an agent. It contains the abilities an agent has to interact with others or make decisions. In other words, an agent-based model is a simulation of the interaction of a set of agents over time that make decisions based on their goals, exogenous parameters and past interaction with other agents.

A schematic overview of the components of the agent-based model is presented in Figure 4. Agents – making individual decisions – and technological installations make up the core of the model. The decisions of agents are made based on the parameter inputs. The system as a whole evolves based on the decisions of individual agents. After aggregation of results, the outcomes can be analyzed of behaviour of agents and system developments.

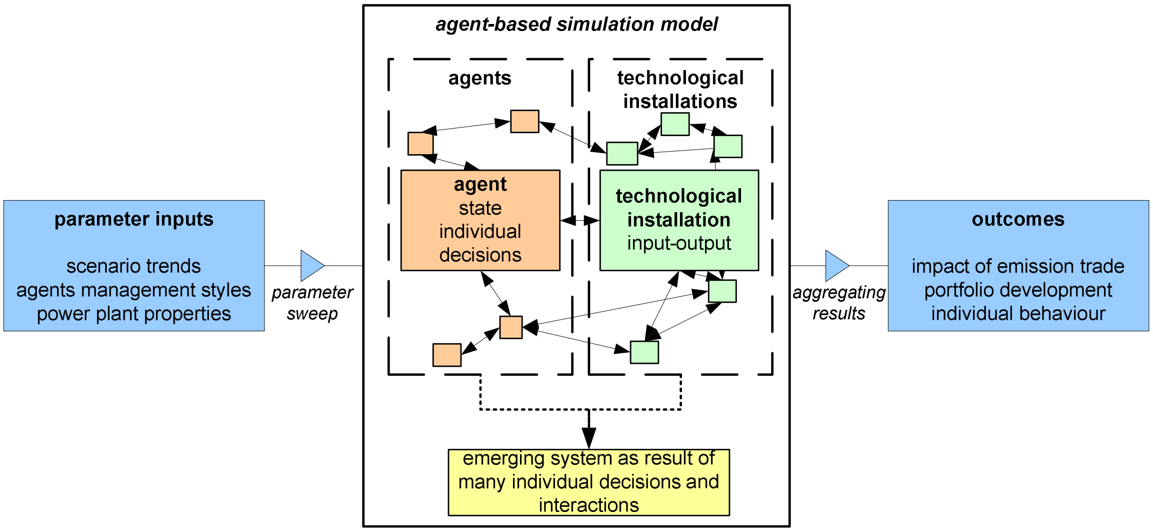

Figure 4. The agent-based model, from parameter inputs to outcomes

The main agents in the model are autonomous power companies, of which six are modelled, each with a unique set of decision criteria to decide on their (dis)investment, production and sale of electricity. The (dis)investment decision is made in three steps:

- deciding what power plants should be dismantled;
- deciding if investing in a new power generation facility is needed;
- deciding which type of electricity generation plant is preferred.

Criteria for divesting are that the technical lifetime of existing power plants is reached and that for some time it is continuously found that marginal revenue cannot cover the marginal costs. Next, criteria for investment are that expiring capacity should be replaced or that there is need for capacity expansion. Consecutively, criteria for selection of electric power generation type include rational criteria, such as the lifetime cost-benefit but also irrational criteria, such as a dislike of nuclear power plants and conservativeness.

Other agents modelled include markets for electricity, fuels and CO_2 emission rights, the government and consumers. In the model electricity can be produced by the combustion of natural gas and coal. In addition, nuclear power and renewable resources can be used.

Power plants can be characterized by their fuel-type, costs, lifetime and fuel usage. In Table 2, the main characteristics of the used power plants in the Netherlands are listed. For coal, two types are listed, a conventional coal fired steam power plant and a clean coal power plant in which the CO_2 emission is stored in an empty gas field. Only the last type of power plant is not yet proven technology, but seen as one of the most promising technologies (Task Force Energietransitie 2006). Operational flexibility in power plants is limited. Since reductions by changes in existing power plants are assumed to be of limited impact, in the model emission reduction can only be realized by a shift in the power generation portfolio used.

Table 2. Main properties of power plants in the Netherlands (Chappin 2006).

type	*lifetime [year]*	*capacity ranges [MW_e]*	*construction costs [€ MW_e^{-1}]*	*fuel usage [kWh_e^{-1}]*
nuclear	40	550 – 2000	2,000,000	2.00 x 10^{-5} [ton]
CCGT (natural gas)	30	1000 – 2250	500,000	222 [m^3]
CFSTP (coal)	30	1000 – 2000	1,250,000	0.276 [ton]
wind	25	100 – 2250	1,150,000	n/a
clean coal	30	1000 – 2000	2,000,000	0.276 [ton]
biomass	30	100 – 225	1,250,000	0.276 [ton]

The agents' decisions are based on factors, not influenced by the model. Those factors are modelled as environment scenarios (Enserink *et al.* 2002). Three driving forces are defined that have an effect on relevant and uncertain factors surrounding the agents, namely world economic growth, environment mindedness and external limitations. The factors influences include potential developments in fuel prices, electricity demand and changes in the cap. For all factors, data were collected for initial values and trends (Chappin 2006), reported in Table 3. The three scenario axis together build a scenario space – a cube – in which each point is represents set of values of trends, in other words, a scenario. A total of 9 scenarios are selected: all combinations of extremes on the axis and one in the centre of the scenario space (see Figure 5).

Table 3. Scenario data values and trends.

scenario axes	*factors influenced*	*initial value*	*high trend*	*low trend*
world economic growth	aggregate electricity demand	106 TWh	+ 4%/year	+ 0%/year
	average margins in supply bids	*constant*	15%	5%
	CO_2 right demand of other industry	*constant*	10 Mton	0 Mton
	natural gas price	0.144 €/m^3	+ 6%/year	+ 2%/year
	coal price	52.6 €/ton	+ 3%/year	+ 1%/year
	uranium price	40 €/kg	+ 5%/year	+ 1%/year
	bio-fuel price	66 €/ton	+ 2%/year	+ 0%/year
environment mindedness	amount of JI/CDM allowances bought	*constant*	10 Mton/year	0 Mton/year
	technology specific subsidies	*constant*	100 €/MW	0 €/MW
external limitations	cap width	50 Mton	- 2%/year	+ 0%/year
	part of rights grandfathered	*constant*	70%	90%
	electricity import price	15 €/MWh	+ 2%/year	+ 0%/year
	inter-connector capacity	20 TWh	+ 0%/year	+ 2%/year
	types of power plants available	*constant*	no cln coal	all

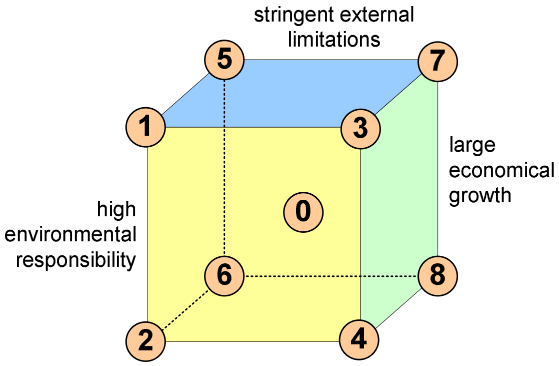

Figure 5. Scenario space

An electricity market agent represents the daily APX spot market and the longer term bilateral contracts. Yearly output and prices are calculated based on yearly bids that power producers make for its installations and the yearly demand, import price and capacity and the aggregate demand by using the following formulas:

$$s_i = \begin{cases} c_i \times \dfrac{d}{\sum_{j=1}^{n} c_j} \times \dfrac{\sum_{j=1}^{n}\left(c_j \times p_{b,j}\right)}{\sum_{j=1}^{n} c_j \times p_{b,i}} & \text{for } \dfrac{\sum_{j=1}^{n}\left(c_j \times p_{b,j}\right)}{\sum_{j=1}^{n} c_j \times p_{b,i}} < 1 \\ c_i & \text{for } \dfrac{\sum_{j=1}^{n}\left(c_j \times p_{b,j}\right)}{\sum_{j=1}^{n} c_j \times p_{b,i}} \geq 1 \end{cases} \tag{1}$$

$$p_{a,i} = 40 \times \frac{d}{\sum_{j=1}^{n} c_j} \times \frac{\sum_{j=1}^{n}\left(c_j \times p_{b,j}\right)}{\sum_{j=1}^{n} c_j \times p_{b,i}} \tag{2}$$

Where s_i is the actual supply of power plant i in MWh_e /year, c_i is the capacity power plant i in MWh_e/year, $p_{a,i}$ is the actual price for power plant i in €/MWh_e, $p_{b,i}$ is the bid for power plant i in €/MWh_e, d is the total demand for electricity in MWh_e/year and n is the number of power plants. Bids are based on marginal costs. Relatively low bids result in low electricity price and base load. Relatively high bids lead to a higher price and peak load. The electricity price is based on supply and demand, on the relative bid height and a correction factor to calibrate for real prices

The allocation scheme defines the amount of rights that are grandfathered per CO_2 emitting installation:

$$g_i = t \times \frac{r}{100} \times \frac{e_i}{\sum_{j=1}^{m} e_j} \tag{3}$$

Where g_i is the number of grandfathered rights for agent i in €/ton, t is the total cap in ton/year, r is the percentage of total rights that are grandfathered, e_i is the actual emission by the installations of agent i in ton/year and m is the number of agents. The allocation scheme limits the total amount of rights – a cap-and-trade system – and the part of the total that is grandfathered. The available rights are divided amongst the electricity producing agents on basis of actual emissions. Prices are equal for all parties:

$$p_{CO_2} = 10 + 40 \times \left(\frac{\sum_{j=1}^{n} e_j}{t} \right)^2 \tag{4}$$

Where p_{CO2} is the price of CO_2 rights in €/ton, e_j is the emission of power plant j in €/ton, n is the number of power plants and t is the total cap in ton/year. The price is based on ratio of supply and demand for emission rights and the total emission of the sector. The price is calibrated at a base price of 10 €/ton CO_2 and a price of 50 €/ton CO_2 when using of all domestic rights.

The model has been implemented using the ABM framework developed by Nikolic et al (Nikolic & Dijkema 2006; Nikolic *et al.* 2007). A shared ontology – a formalized structure of concepts with a knowledge base – therein built in Protégé (Protégé 2006) was used to define the power companies as agents, their power producing facilities and the available technologies. The source code for the model was written in the integrated development environment, Eclipse (Eclipse 2006) in Java (Sun Microsystems 2006). In addition, Repast was used as agent-based simulation tool (Repast 2006). In order to obtain a robust image of CET-impact parameter sweeps over the entire scenario and parameter space were completed by running some 450 simulations. The results obtained were statistically analyzed by using SPSS (SPSS 2007). In the analyses, no values of single runs were used, but average values over the scenario and parameter space. In Figure 6 an overview of the software tools in the ABM simulation engine framework is given.

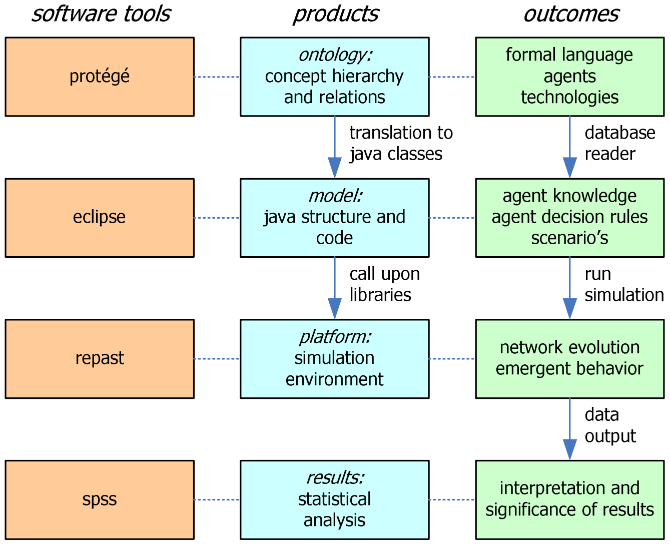

Figure 6. Software tools in the ABM simulation engine framework

Since reductions by changes in existing power plants are assumed to be of limited impact, in the model emission reduction can only be realized by a shift in the power generation portfolio used. The sector will decrease its CO_2 intensity only if the implementation of CET leads to a shift in portfolio. Since electricity generation is liberalized, however, each electricity producer uses its own criteria to decide on their (dis)investments. In addition, it may be expected that the portfolio shifts only gradually, as power plants have a technical and economic lifespan measured in decades. Therefore, the attention in the outcomes goes – next to CO_2 emissions – to the changes in portfolio.

Model validation and simulation outcomes

Extensively validation was done during and after development of the model. Since for agent-based models no generally accepted validation methods are in the literature for validation of agent-based models many of the same tests developed for System Dynamics models are used, following Qudrat-Ullah (2005, page 2). Even a broader range of validating methods for System Dynamic Models is used than he suggested, where applicable, the tests are used that Barlas (1996) described. The executed tests include direct structure tests, such as tests on empirical structure and parameters, direct extreme conditions, boundary adequacy of structure, dimension analysis and face validation. Also structure oriented behaviour tests were successfully completed: tests for extreme conditions, qualitative future analysis, comparison with accepted theory and an extensive sensitivity analysis. After validation, over a thousand simulations are executed over the extensive scenario-space described earlier, each with a time period of 75 years. Initial conditions for all simulation runs are equal, but the modelled variation in scenarios and the modelled uncertainty leads to variation in the output. Also simulations were done in which emission-trading was not present. The simulation outcomes are statistically analyzed and aggregated to provide meaningful results.

The impact of CO_2 emission-trading on emissions is shown in Figure 7. The emission reduction over time is depicted that is a consequence of the implementation of CET. A value of 25% for scenario *x* at year *y* means that when during the time up to year *y* CET was not implemented, the emissions by electric power generation would on average for scenario *x* by 25% higher. Each deviation from 0% is thus a consequence

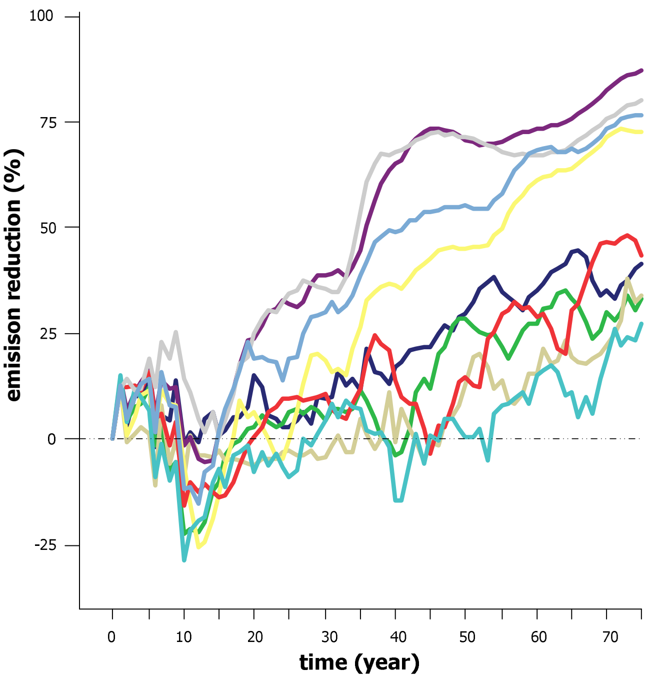

Figure 7. The average impact of CO_2 emission-trading on emissions in different scenarios

of CET. As shown, the impact in the first two decades is small: for some scenarios a reduction and for others an increase of up to 25% is noted. After that, a significant reduction is reached in most scenarios. Reductions can reach even 80% on the long term. However, absolute emissions still rise under most scenarios, since total electricity demand rises.

In Figure 8 the composition of the electricity generation portfolio over time is displayed averaged over all scenarios and runs: this assumes that all scenarios have equal probabilities to actually occur. In the graph, the brightest colours show the developments under the emission-trading system. Also the developments are

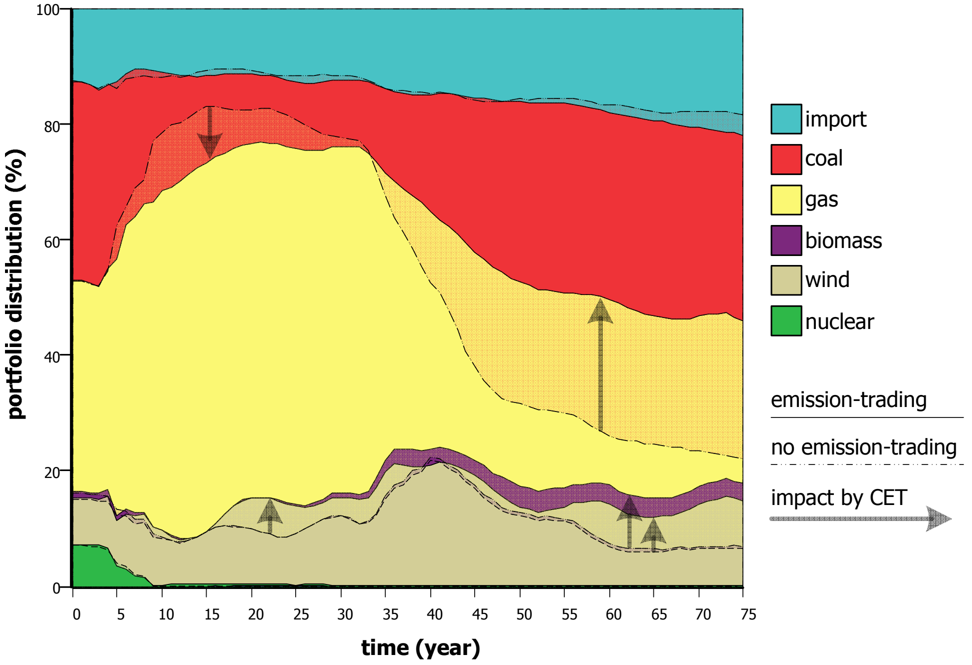

Figure 8. The average impact of CO_2 emission-trading on developments in portfolio composition

drawn in a system where emission-trading is absent: in dotted lines and faded colours. An impact is clearly shown: developments in the composition of the electric power generation portfolio differ. In the first decades the impact is minimal: current standing installations are not replaced until the physical lifetime has passed and electric power producers just accept the costs for CO_2 rights. Even the current run for natural gas power plants is slowed down. After the first decades, a shift is noted towards coal, although its emission-intensity is highest of all. However, the shift to coal would be even stronger without emission-trading. Renewable sources are used more, but power producers withhold to adopt them significantly, even on the long term. The effect of CET is thus not strong enough.

As was mentioned, unique sets of investment decision criteria were selected for six electric power producer agents in the model. At this moment, the criteria are fixed within and between runs. The examples in Figure 9 show that the portfolios of the agents develop differently, although on average coming from equal initial portfolio compositions. It was found that electricity producer 3 had the highest power generation capacity at all times and was also most profitable. Since this producer is in the model the largest emitter– since it uses the most coal of all agents and only little amounts of renewable sources – and the most profitable (!) it is not likely that emission trading has a strong enough price-signal to generate a total shift, especially since in reality decision criteria might change over time towards the criteria of the more successful power producers.

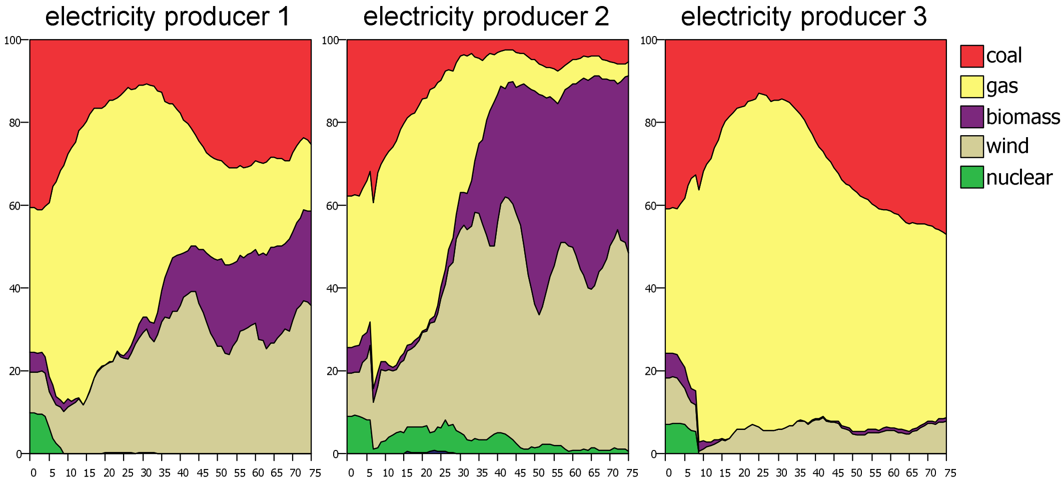

Figure 9. Portfolio developments of individual electric power producers

Conclusions and implications

The impact of CET on emissions by Dutch power production and its generation portfolio is relatively small and late: absolute emissions by electricity generation rise under most scenarios. On the longer term a shift towards coal is found, driven by low coal costs and an increase in electricity demand. From these results it should not be interpreted that the presented portfolio developments will be most likely to occur. Large differences between scenarios are found, technological innovation will drive down fixed and/or variable costs for alternatives and new alternatives might be developed, new power producers can come to the market and existing can merge or adapt their strategies. However, a model incorporating those issues is on the research agenda and might give more concrete insight in developments of the power generation portfolio.

The findings correspond to the dominant part of current capacity expansions plans in the Netherlands and Germany. An overview of plans for new power plants in these two countries is given in Table 4, calculated per fuel type. For some coal power plants planned for the Netherlands it is possible to co-fire biomass with the coal (the figures are calculated with a maximum of 15% co-fired, on basis of energy). In the Netherlands, in the coming years much capacity for natural gas will become operational. However, starting from 2010, large coal power plants are planned – modernized, but still the most CO_2 intensive option available – amounts probably exceeding the natural gas capacity planned (46-52% of total planned capacity). In Germany this is even worse: 68% of their plans are to build coal power plants. This equals 30 GW_e which corresponds to 1½ times the Dutch capacity at this moment. Also in the UK, the first coal power plant in 20 years is planned for after 2010 (The Parliamentary Office of Science and Technology 2007). It seems surprising that even after the introduction of CET current power generation capacity expansion plans indicate a preference for coal. Apparently the economic effect of CO_2 emission-trading is not sufficient to outweigh the incentives to choose for coal. As also comes out of the model, such a shift is not easily reversed: power plants have lifetimes of decades.

Table 4. Plans for new power plants in the Netherlands and Germany, calculations based on public sources (RWE 2007; Seebregts 2007)

country	*energy source*	*capacity [MW_e]*	*% of plans per country*	*operational in*
the Netherlands	natural gas	4,390	45.6%	2008-2010
	coal	4,415-5,000	45.9 – 52.0%	2011-2012
	biomass	< 685	< 7.1%	2008-2013
	offshore wind	228	2.4%	2006-2007
	total	*9,618*		
Germany	natural gas	12,830	29.7%	2007-unknown
	coal	29,245	67.6%	2008-unknown
	nuclear	60	0.14%	2007-unknown
	other	1,102	2.55%	2007-unknown
	total	*43,237*		

References

AXELROD, R. 1997. Advancing the Art of Simulation in the Social Sciences. *Simulating social phenomena*. R. Conte, R. Hegselmann and P. Terna. Berlin ; New York, Springer**:** 21-40.

BARLAS, Y. 1996. "Formal Aspects of Model validity and validation in system dynamics." *System Dynamics Review* **12**(3): 183-210.

BUSSMANN, S., N. R. JENNINGS & M. WOOLDRIDGE 1998. *Multiagent Systems for Manufacturing Control*. Berlin, Springer.

CHAPPIN, E. J. L. 2006. Carbon Dioxide Emission Trade Impact on Power Generation Portfolio, Agent-based Modelling to Elucidate Influences of Emission Trading on Investments in Dutch Electricity Generation. Delft, Delft University of Technology.

COZIJNSEN, J. 2005. "Website over emissiehandel." Retrieved December 19, 2005, from http://www.emissierechten.nl.

ECLIPSE. 2006. "Eclipse.org home." Retrieved February 23, 2006, from http://www.eclipse.org.

EHRHART, K. M., C. HOPPE, J. SCHLEICH & S. SEIFERT 2003. "Strategic aspects of CO2-emissions trading: Theoretical concepts and empirical findings." *Energy and Environment* **14**(5): 579-598.

ENERGIENED. 2006. "EnergieNed." Retrieved February 23, 2006, from http://www.energiened.nl/.

ENSERINK, B., J. F. M. KOPPENJAN & W. A. H. THISSEN 2002. *Analyse van Complexe Omgevingen, leerboek*. Delft, TBM TU Delft.

EPSTEIN, J. M. & R. AXTELL 1996. *Growing artificial societies: social science from the bottom up*. Washington, D.C., Brookings Institution Press; MIT Press.

EUROPESE UNIE. 2004, November 15. "ScadPlus: Regeling voor de handel in broeikasgasemissierechten." Retrieved January 25, 2006, from http://europa.eu.int/scadplus/leg/nl/lvb/l28012.htm.

JENNINGS, N. R. 2000. "On agent-based software engineering." *Artificial Intelligence* **117**(2): 277-296.

NIKOLIC, I. & G. P. J. DIJKEMA 2006. Shaping Regional Industry-Infrastructure Networks - An Agent Based Modelling Framework. *2006 IEEE Conference on Systems, Man, and Cybernetics*. Taipei, Taiwan**:** 901-905.

NIKOLIC, I., G. P. J. DIJKEMA & K. H. V. DAM 2007. Understanding and Shaping the Evolution of Sustainable Large-Scale Socio-Technical Systems, Towards a Framework for Action Oriented Industrial Ecology. *Dynamics of Industrial Ecosystems*, Reviewed and accepted.

OTTENS, M., M. FRANSSEN, P. KROES & I. VAN DE POEL 2006. "Modelling infrastructures as socio-technical systems." *International Journal of Critical Infrastructures* **2**(2-3): 133-145.

PROTÉGÉ. 2006. "The Protégé Ontology Editor and Knowledge Acquisition System." Retrieved February 23, 2006, from http://protege.stanford.edu.

QUDRAT-ULLAH, H. 2005. *Structural Validation of system dynamics and agent-based simulation models.* 19th European Conference on Modelling and Simulation, Riga, Latvia.

REPAST. 2006. "Repast Agent Simulation Toolkit." Retrieved 2006, February 23, from http://repast.sourceforge.net.

RWE. 2007. "RWE Facts & Figures 2007." from http://www3.rwecom.geber.at/factbook/en/servicepages/downloads/files/electricity_generation_rwecom_fact07.pdf.

SEEBREGTS, A. J. 2007. "Beoordeling nieuwbouwplannen elektriciteitscentrales in relatie tot de WLO SE- en GE-scenario's: een quickscan." from http://www.ecn.nl/docs/library/report/2007/e07014.pdf.

SMITH, A. 1776. *An Inquiry into the Nature and Causes of the Wealth of Nations*

SPSS. 2007. "SPSS, Data Mining, Statistical Analysis Software, Predictive Analysis, Predictive Analytics, Decision Support Systems." from http://www.spss.com/.

SUN MICROSYSTEMS, I. 2006. "JavaTM 2 Platform Standard Edition 5.0 API Specification." Retrieved May 8, 2006, from http://java.sun.com/j2se/1.5.0/docs/api.

SVENDSEN, G. T. 1999. "The idea of global CO2 trade." *European Environment* **9**(6): 232-237.

SVENDSEN, G. T. & M. VESTERDAL 2003. "How to design greenhouse gas trading in the EU?" *Energy Policy* **31**(14): 1531-1539.

TASK FORCE ENERGIETRANSITIE 2006. More with Energy, Opportunities for the Netherlands. Utrecht, SenterNovem.

THE PARLIAMENTARY OFFICE OF SCIENCE AND TECHNOLOGY. 2007. "Electricity in the UK." from www.iop.org/activity/policy/Publications/file_21079.pdf.

UNFCCC 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change.

VRIES, L. J. D. 2004. Securing the public interest in electricity generation markets, The myths of the invisible hand and the copper plate. *TBM*. Delft, TU Delft. **PhD**.

WEISS, G. 2000. *Multiagent systems, a modern approach to distributed artificial intelligence*. Cambridge, Mass., MIT Press.