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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 the agreed 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 to an amount equal to their CO_2 emission. In Europe, electricity generation accounts for one-third of CO_2 emissions. Since the power generation sector, has been liberalized, reregulated and privatized in the last decade, around Europe autonomous companies determine the sectors' CO_2 emission. Short-term they adjust their operation, long-term they decide on (dis)investment in power generation facilities and technology selection. An agent-based model is presented to elucidate the effect of CET on the decisions of power companies in an oligopolistic market. Simulations over an extensive scenario-space show that there CET does have an impact. A long-term portfolio shift towards less-CO_2 intensive power generation is observed. However, the effect of CET is relatively small and materializes late. Under most scenarios the absolute emissions from power generation rise under most scenarios. This corresponds to the dominant character of current capacity expansion planned in the Netherlands (50%) and in Germany (68%), where companies have announced many new coal based power plants. Coal is the most CO_2 intensive option available and it seems surprising that even after the introduction of CET these capacity expansion plans indicate a preference for coal. Apparently in power generation the economic effect of CO_2 emission-trading is not sufficient to outweigh the economic incentives to choose for coal.

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

1. Introduction

Under the Kyoto Protocol, governments agreed on and accepted CO_2 reduction targets in order to counter climate change [1]. 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`; 2]. 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 [3]. 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 Member States must make sure a suitable price of rights is formed and that 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 [4; 5; 6; 7].

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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 [8]. It may thus be seen the power sector is pivotal to CET. In the past decade this sector has been liberalized, reregulated and privatized in the last decade. Today power generation is separated from electricity transport and retail and supply. Relatively few, autonomous companies are in the business of large-scale power generation. They must survive in oligopolistic but competitive market-conditions. Options to reduce their CO_2 emission include short-term adjustment of their operation, medium-term revamp and long-term they may decide on investment and divestment in power generation facilities and technology selection.

Although the operational flexibility of power generation facilities designed for base-load operation is limited, CET will certainly stipulate further optimisation of power plant optimization. The net effect on CO_2 emission is important, but an order of magnitude smaller than the possible effect of (dis)investment decisions: a coal-fire power plant emits 2.5-3 times the amount of CO_2/MWh of a gas-fired plant. The CO_2 emissions of wind-farms and nuclear plants are negligible. Moreover, all of these capital-intensive facilities currently have technical and economic life-spans of 25-40 years, so decisions today will determine CO_2 emissions for decades. Markets served by capital-intensive facilities are known to be cyclic; the investment in a large-scale power plants may require an investment between 500 and 1500 Million Euros. Switching cost thus are high. While an emission market arguably would lead to reduction at the lowest cost, it remains to be seen whether sufficient emission reduction is achieved long-term.

The central question in this paper therefore 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 simulation model. The paper is structured as follows. First, emission-trading, electric power production and the system perspective used are elaborated upon. Subsequently, the agent-based model setup and implementation are explained in detail. Third, model validation, assumptions and limitations are given. Fourth, the simulation results are presented and analysed. Finally, conclusions are drawn.

2. Background and system perspective

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

This paper focuses on the electric power generation sector. A socio-technical systems-perspective is adopted to analyze the long-term effect of CET on this system [9]. In this perspective, the sector is viewed as a single system that consists of a technical and social subsystem. The technical subsystem contains physical apparatus, such as power generation facilities, electricity grids and consumer equipment; the laws of physics apply to this subsystem and its components. The social subsystem contains actors who engage in contracts with each other on the exchange of fuel, electricity and emission-rights. Some of these actors own and operate components of the physical subsystem. This social system is subject to a regulatory regime and market competition. To survive and make sufficient profits the actors must decide on the operation of their assets, secure fuel at a suitable price, make or defer investment decisions and select the technology they want to use. In Figure 1 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: in many a country a tight oligopoly is in place [10]. 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 [3]. In Table 1, the main characteristics of the energy sources are stated.

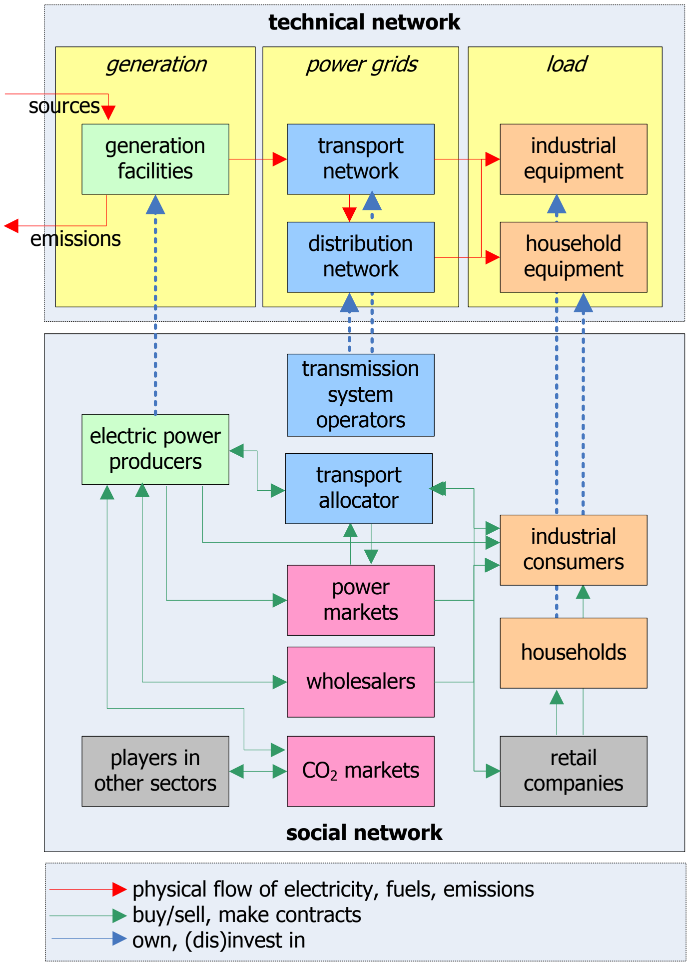

Figure 1. Socio-technical system of electricity production and emission-trading

Table 1. Characteristics of energy sources and their adoption in the Netherlands.

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%

CO_2 emissions are energy source dependent: coal is the most CO_2 intensive; gas is less CO_2 intensive nuclear and wind are essentially CO_2-free. Contrary to the carbon-intensity, coal is a relatively cheap fuel compared to natural gas. Uranium can be acquired at even lower cost, if compared on an energy basis. When it comes to investment, on a per MW basis a world-scale gas-fired power plant has the lowest investment; a modern coal plant requires is about twice as expensive, a modern nuclear plant is more than 5 times as expensive.

Biomass is the subject of an intense debate wherein its carbon-neutrality is questioned [11]. Under the current EU CET biomass is considered to be carbon-free, on the basis of the notion that firing biomass implies that only short-cycle carbon is used and the carbon uptake of the biomass chain equals the carbon emission. Recently, however, it has been concluded by a variety of researchers and the Cramer Commission [12] that first generation biomass use does have a carbon footprint of 30 to 70% of the carbon in the biomass used. Technology used is similar to a coal-fired plant, so also the per MW investment of a biomass plant is similar.

Electricity is transported long-distance over a high voltage transport grid that is owned and controlled by system operators. Medium voltage distribution grids are used for local distribution.

Ownership and control of these networks varies throughout Europe. 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, mainly through engaging in bilateral contracts with electricity generators. It is this bilateral market which is the main power market in the Netherlands, where 80% of the electricity is exchanged. 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), it may be seen that a net reduction of emission from the sector is hard to achieve. The reasons for this are the following:

- The demand for electricity has been rising steadily by 2% per year on average for the last decades. The continuous increase in population and living standards are the main underlying reasons. The growth reflects the ongoing electrification of society.
- The demand for electricity is relatively inelastic to changes in the price [13]. Electricity from the grid continues to be a superior product and apparently to many a consumer the costs remain to low to provide an economic incentive. Presently, the incentives for consumers to invest in low-energy devices or sustainable distributed generation apparently are not sufficiently attractive.
- End-users are connected to the grid and their demand is relatively price-inelastic. Thus they can be considered price-takers. Thus, instead of switching to low-carbon generation, electricity producers may decide to include the CO_2-costs in their price.
- Due to the market structure, CO_2 price signals *to consumers* are dampened or reversed. The first-order effect of CET is to affect the bid prices of all electricity suppliers. This leads to two responses: First, an increase in electricity prices leads to a decrease in demand expressed in the market. Since – especially on the short term – demand is inelastic to price, this effect is small. Second, in the exchange markets the attractiveness of suppliers shifts towards less CO_2 intensive electricity producers. When emissions are priced, all else being equal, these can offer electricity at a lower price than CO_2 intensive producers, but only for the volumes they can produce. In order to compete, CO_2 intense producers may have to lower their profit margin and reduce their price somewhat for part of their volumes sold. The net result is that consumers may experience a somewhat lower price, while the major part of the bilateral market remains to be served by CO_2 intense producers.

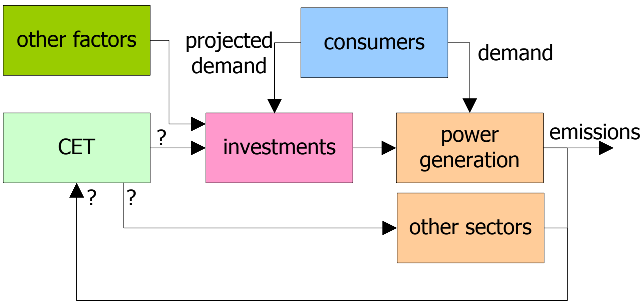

Figure 2. The effect of CET on electricity generation

It may thus be seen it is not implicit that through CET the sector's CO_2 emission would reduce dramatically.

Given the probability of continued modest demand growth, or maybe stabilisation of demand volume, the inelasticity of demand and weak price signals to consumers, the CO_2 intensity of electricity *generation* should decline significantly to achieve a net decrease of emissions mid- to long term. The operational flexibility of power plants is limited, however, and thus the CO_2 intensity of currently operating equipment can only be decreased marginally. 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); The switching costs incurred are high, as power plants are capital-intensive, long-lived installations.
- by innovative technologies that have lower costs operational and lower CO2 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 2).

3. Model description

To elucidate the impact of CET on the power generation sector's CO_2 emission an agent-based model (ABM) was built of this socio-technical system. In the model, actors are represented by agents that live in a simulated world driven by exogenous forces (Figure 3). The agents represent companies active in electricity production. They own and operate a set of power generation facilities, the technical system. Each generation facility is represented in the model by a set of equations that respect the Law of conservation of Mass and Energy. The agents' behaviour is modelled by a set of rules, which reflects the way operating and (dis)investment decisions are made in the power industry.

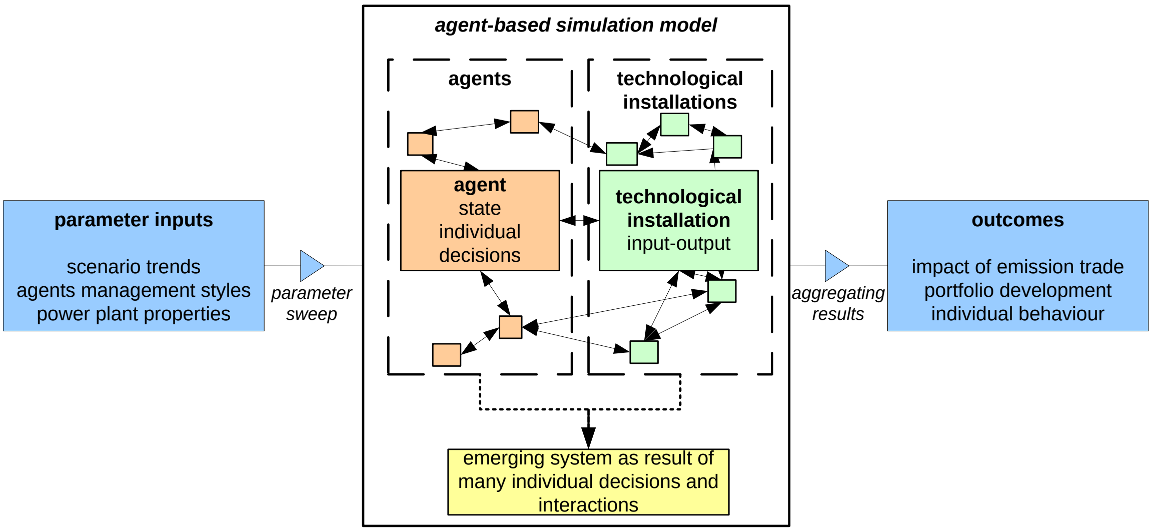

Figure 3. The agent-based model, from parameter inputs to outcomes

Agent Based Modelling

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" [14; 15]. 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" [16]. Although in the literature different sets of properties for agents are proposed [17; 18], 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 3. Agents – each 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 with respect to the behaviour of agents and system developments.

The agents in the model do strategic management; they must make decisions which have a large and long-lasting impact. The agents also do operational management, as they must deal with day-to-day operational decisions. Those two different types of decision making are modelled and discussed separately. The reasons for this distinct model setup and the implications for model implementation have been extensively documented elsewhere [19].

Simulation schedule and agent interaction

Although the agents are central in the model, there is a simulation schedule that aligns the agents in their actions and interactions. The simulation schedule consists of four steps:

- *Model initialization*. Determines whether a single run or a set of batch runs is performed and what output is selected. When single run mode is selected, model parameters can be adjusted. When batch run mode is selected, the variety of parameters must be selected to define the particular scenario-space for this set of runs. After run type selection, the model dataset is loaded from the knowledge base (see below for more details and implementation issues).
- *Run initialization*. In this step, the dataset is used to initialize the run, whether single, or one of a batch runs. The selected parameters together with the data from the knowledge base determine what agents and technological installations are created. That means among other things that the initial portfolio of power plants is created in this step. Also the initial scenario parameters are selected and applied.
- *Simulation*. The agents evolve over time by action and interaction and by exogenous change. The total simulation run length of 75 years is sliced into steps of one year. Each step, the model procedure is repeated until the end of the simulated period is reached.
- *Next run*. If a set of batch runs is to be completed, the next run is then initialized, i.e. Run initialization step is executed again and a new simulation is completed.

In each simulation run, the system behaviour is the combined result of the actions of all agents. For instance, the electricity prices and supplied amounts from the installations are the result of the electricity trading step, in which based on the bids that all electricity producing agents did the market clears (see explanation below). The simulation is essentially demand driven. Since there is demand for electricity, there is demand for fuels and emission rights. As time passes, installations reach the end of their technical or economic lifespan and a demand for new investment emerges. In case demand grows rapidly, opportunities for investment arise earlier in the simulation run. The choice of the demand pattern over the simulation run basically determines the order of actions and interactions and how they are aligned.

The agent’s decision making is implemented in the model procedure, which is used in each simulation run. The main calculation steps in this procedure are:

- Update exogenous scenario parameters.
- Electricity trading
- Emission trading
- Fuel trading
- Investment and divestment
- Update graphics

The agents and their decision making are described below.

Power producing agents

The main agents in the model are *power producing companies*. To reflect the tight oligopoly, the number of them is set to 6. Each of them has the same decision making *structure*, but differ in *management style* (see below). The agents have strategic management in which they decide on divestment and investment.

- *Divestment.* The agents decide what power plants should be dismantled. Two reasons for divestment are modelled: (1) reaching the technical lifetime of existing power plants and (2) for a long time (5-9 years, dependent on the agents’ management style) marginal revenue has been smaller than marginal costs.

- *Investment.* The agents decide if investing in a new power generation facility is sufficiently attractive to them. The reasons for investment are (1) to-be-expired capacity will be replaced and (2) an opportunity for capacity expansion is identified.
- *Technology type.* If agents decide to invest, they will also decide on the preferred technology type for investment. In the simulation model, their decision is assumed to be based on a multi-criteria analysis (MCA). Therein, criteria used for selection of the electric power generation type include hard and soft criteria. The lifetime cost-benefit expectation is a hard criterion, for which all anticipated costs and revenues are modelled: investment cost, fuel, CO_2 and other variable costs, and revenue from power generation . Soft criteria such as a dislike of nuclear power plants and conservativeness are also taken into consideration. The performance of all possible alternative technologies on all criteria will be calculated for each agent using score weights that reflect the agent's management style. The analysis leads to a single best alternative. See [19] for a more elaborate description of the implementation of MCA in the agents.

As stated, apart from strategic management , the power producing agents have operational management. Short-term, they must make decisions on:

- *Selling of electricity.* Based on marginal costs bids, agents sell electricity through the spot market for electricity; the spot market, the APX, is represented as another agent in the simulation, which is described below. Marginal cost bids are based on expected fuel cost, other variable cost and CO_2 cost. The expected CO_2 cost are based on past CO_2 prices on emission right market (see below).
- *Acquiring fuel.* Based on actual electricity production, the needed fuel is determined and acquired.
- *Acquiring CO_2 rights.* Based on actual electricity production, the needed emission rights are acquired.

Other agents

Other agents modelled include the markets for electricity, CO_2 emission rights, the government, a market for fuels and electricity import, an aggregate consumer agent and an environment agent.

Electricity spot market. All electricity is sold through the electricity spot market agent. This agent represents the combination of an ordinary day-ahead spot market, such as the Dutch APX market and the longer term bilateral contracts. The agent collects all bids from electricity producers. In addition it collects information related to import from the world market agent (see below) and demand from the aggregate consumer agent (see below).

The electricity spot market agents' decision-making comprises the market clearing process. In reality, spot markets operate on a very short transaction horizon, e.g. quarter of an hour. To limit the required computational time, this is aggregated to a yearly clearing process. The clearing process implemented takes into account the variation of demand over the day and the year, i.e. it reflects the price-differences for base-load and peak–load electricity. 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:

$$s_i = \begin{cases} c_i \times \dfrac{d}{\sum_{j=1}^{n} c_j} \times \dfrac{\sum_{j=1}^{n}\left(c_j \times p_{b,j}\right)}{\sum_{j=1}^{n} c_j \times p_{b,i}} & \text{for } \dfrac{\sum_{j=1}^{n}\left(c_j \times p_{b,j}\right)}{\sum_{j=1}^{n} c_j \times p_{b,i}} < 1 \\[2em] c_i & \text{for } \dfrac{\sum_{j=1}^{n}\left(c_j \times p_{b,j}\right)}{\sum_{j=1}^{n} c_j \times p_{b,i}} \geq 1 \end{cases} \tag{1}$$

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

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.

The first formula determines the actual yearly supply per installation, by using bid price and capacity. Since bids are based on marginal costs, as stated above, relatively low bids already result in relatively high actual supply offers: these bids will be for base load. The reason behind this is that by accepting these low price – high volume bids, an installations produce will be in merit (below the market clearing price) for a greater part of the year and will thus produce more. The second formula determines the price, also according to the bid. Relatively high bids lead to a higher price. The rational for this formula is that at a high bid the average selling price is higher because the market prices under which you were in merit are only the high prices. A validation of these formulas can be found in [20], appendix E.

After market clearing, contracts are signed and finalized. The agents involved in a particular bid make sure themselves that the actual electricity is supplied according to the contract and that the financial transaction is completed.

Government. In the simulation model there is one government agent that makes policy related decisions. Under the emission trading scheme, it decides on *allocation*: whether and how to distribute emission rights at no cost, so called grandfathered rights. By the following formula, grandfathered rights are allocated for a single installation, when the emitting agent demands them:

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

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 (for instance 90%, the rest should be acquired from the market). The available rights are divided amongst the electricity producing agents on basis of actual emissions. Therefore each agent gets its share. This reflects the arrangement for grandfather adopted in the first and second phase of the EU ETS.

Emission market. Since it is often the case that agents need more rights then they obtain from grandfathering, additional emission rights can be acquired from the emission market agent. Yearly clearing is based on the demand for and the supply of rights. Prices are equal for all parties and are based on the following calculation:

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

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 rights assigned for the power generation sector. The main assumption in this setup is to reflect the main idea of ETS, namely that inter-sector trade should be possible to achieve emission-reductions in sectors that incur the lowest cost. The implication is that a reduction of the sector emission to comply with the amount assigned for the sector is *not* necessary: rights can be acquired from other sectors or 'imported' from other countries. This choice has consequences for the impact of CET, both in reality and in the simulation, because it is possible for the sector to grow beyond its cap.

World market for fuels and power import. All fuels can be acquired from the world market agent. This agent sells the fuels available in the model - coal, natural gas, biomass and uranium - at an exogenous price that is determined in the scenario (see below). Since the world market agent is the only agent that offers fuels, the electricity producing agents will buy from this agent at the scenario price. In addition, the world market agent allows for import, but the import capacity is limited. The capacity and import price is set in the scenario.

Aggregate consumer. One single consumer agent corresponds to the aggregate demand of all domestic consumers for electricity. The yearly demand is determined in the scenario (see below).

Environment agent. The last agent is the representation of the environment. The environment agent will supply all environmental uptakes, e.g. air, and consume all environmental emissions such as CO_2. This agent is required to ensure mass and energy balances are correct.

Power plants

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 coal power plant with CCS (Carbon Capture and Storage), i.e. a clean coal power plant. Today, CCS is not yet proven technology, but seen as one of the most promising technologies [21]. Technological innovation is not modelled, except for the possibility of CCS. The operational flexibility of power plants is limited in reality. In the model, operational flexibility is assumed to be negligible. Reductions by operational changes in existing power plants can safely be assumed to be of limited impact. In the model, emission reduction can only be realized by a shift in the power generation portfolio employed.

Table 2. Main properties of the power plants in the model [20].

Type	*lifetime [year]*	*capacity ranges [MW$_e$]*	*construction costs [€ MW$_e^{-1}$]*	*variable costs [€ MWh$_e^{-1}$]*	*fuel usage [kWh$_e^{-1}$]*
nuclear	40	550 – 2000	2,000,000	5	2.00×10^{-5} [ton]
CCGT (natural gas)	30	1000 – 2250	500,000	2	222 [m^3]
CFSTP (coal)	30	1000 – 2000	1,250,000	3	0.276 [ton]
wind	25	100 – 2250	1,150,000	3	n/a
clean coal	30	1000 – 2000	2,000,000	10	0.276 [ton]
biomass	30	100 – 225	1,250,000	4	0.276 [ton]

Exogenous scenarios

As pointed out earlier, agents decide based on their style and in response to exogenous factors. All exogenous factors are bundled in so called environment scenarios. [22]. 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 influenced include potential developments in fuel prices, electricity demand and changes in the cap. For all factors, data were collected for initial values and trends [20], 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 4). Note that subsidies are enabled in some scenarios. Therein, subsidies are provided for the use of technologies that use renewable resources, i.e. wind farms and biomass power plants.

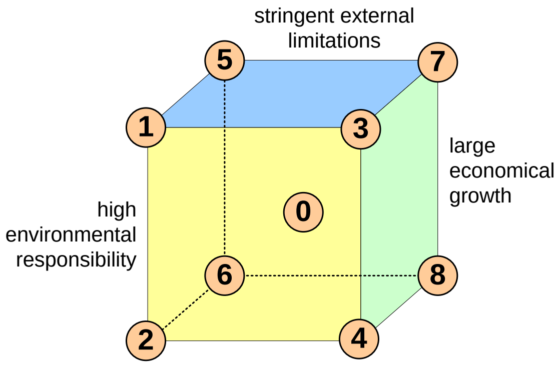

Figure 4. Scenario space

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

Model setup and implementation

The model has been implemented using an ABM framework which was initially developed by Nikolic et al [23] and was further developed during this study [20]. A shared ontology – a formalized structure of concepts with a knowledge base therein – was built in Protégé [24]. This 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 [25] in Java [26]. In addition, Repast was used as agent-based simulation tool [27]. In order to obtain a robust image of CET-impact, parameter sweeps over the entire scenario and parameter space were completed by running some 900 simulations. The results obtained were statistically analyzed by using SPSS [28]. In the analyses reported below, thus no values of single runs were used, but average values over the scenario and parameter space. In Figure 5 an overview of the software tools in the ABM simulation engine framework is given. For a more elaborated discussion on the simulation software stack and the use of an ontology as a knowledge base in ABMs see chapters 4 and 5 in [20].

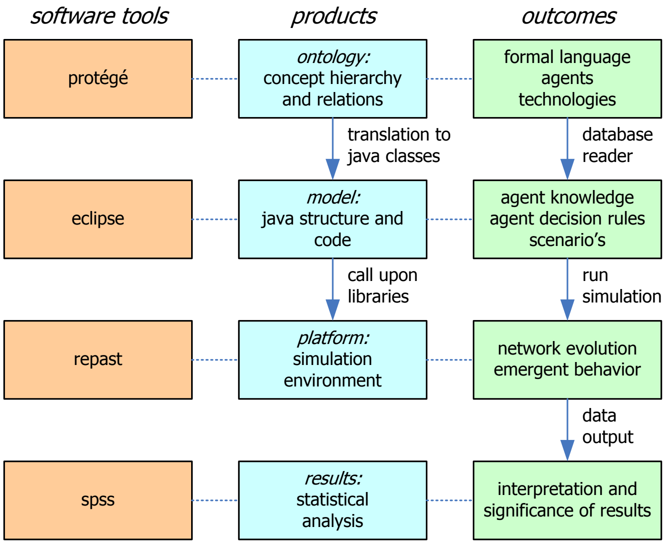

Figure 5. Software tools in the ABM simulation engine framework

4. Model validation and main assumptions

Model validation

Validating ABMs is not straightforward. There are no generally accepted validation methods for ABMs in the literature. Key in this discussion therefore is the definition of a valid model. In this paper *"validity is defined as fit for purpose"* [20`, page 50]. Therefore one can distinguish two parts to validity of the model:

The first part of validity is what we normally refer to as verification, i.e. whether the model is consistent. A consistent model is one in which the objects are modelled free from errors. The second part is on the structure of the model and on conceptual choices and assumptions, i.e. whether the model spans the objects needed and whether it includes a sufficient representation of these objects and their interaction in order to answer the research question(s) that the model was built for.

Extensive validation was performed during and after the model development. for validation of agent-based models many of the same tests developed for System Dynamics models are used, following Qudrat-Ullah [29`, page 2]. Even a broader range of validation methods for System Dynamic Models has been used than suggested in order to validate both on consistency and conceptualization. Where applicable, the tests are used described by Barlas [30]. Our validation approach included 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: these comprise tests for extreme conditions, qualitative future analysis, comparison with accepted theory and an extensive sensitivity analysis. The model outcomes were not sensitive to most parameters, including agents management style parameters. The model seems to be quite sensitive to fuel trends though. It is concluded that except for fuel price trends, the model is not very sensitive to any parameter, since the number of parameters is rather large.

Main assumptions and their consequences

Note that the goal of the model is *not* to provide absolute numbers and predictions, but rather to get insight in the potential of emission-trading as instrument to influence the emissions by power generation through a technology-portfolio-shif over time. Having said that, the main assumptions in the model and their consequences are the following:

Significant technological breakthrough is absent, except for CCS technology. The consequence of this assumption is twofold. First, the overall picture can improve by incremental technological innovations, meaning that both under emission-trading and under a no intervention strategy the emissions might be lower. So the additional insight in the impact of emission-trading is limited. Implementing incremental innovation is on our research agenda in order to potentially model the feedback of higher technology adoption to learning curves, i.e. applying endogenous learning curves [e.g. 31]. Results would change though, if this feedback were significant. Both exogenous and endogenous learning curves are easy to implement within the current framework this is easy to implement, as it will only require small changes in the models' code. Therefore, it is on the research agenda to acquire and implement learning curves. This will be the dealt with in a future publication. The results, in portfolio terms, would not change more than a few percent, because both scenarios with and without emission trading would be impacted in similarly. It would improve results in absolute terms though.

Second, a dramatic technological innovation could occur, the breakthrough of nuclear fusion, for example, could mean a dramatic decline in emissions and outperform all other technologies. Such an outcome is not modelled, since the occurrence of such an innovation is not significantly impacted by the emission-trading scheme and falls beyond the scope of the modelling exercise, i.e. it is not what we want the model to do. What we rather want from the model is to envision the impact that emission-trading has under a realistic set of circumstances. Does emission-trading lead to selection and use of technology that is known and proven today? And does the instrument have sufficient merit - is its impact is large enough to prefer it over alternative policy instruments or no intervention at all?

The model is based on and delineated to the Dutch power and emission markets. Some parameter settings are specific to the Dutch situation. The main features that are Dutch specific are starting portfolio of technologies, the number of power producers, electricity demand, import capacity and general attitude towards nuclear. Obviously, the model would generate different results for parameters corresponding to other countries. The Dutch case is a only a suitable illustration, however. By changing the above mentioned settings and by incorporating the appropriate datasets, all liberalized European power markets, that have limited or no import capacity can be simulated. The Dutch situation is in that sense not more than an exemplary case.

Emission rights can be exchanged between sectors and countries. It is assumed that there are rights available from other sectors and from other countries, basically corresponding to the rules in phase II that started in 2008. One has three options: investing in order to reducing emissions, acquiring rights from the outside and paying the penalty.

However, if one would argue that the amount of rights available for this sector – the imposed sectors' cap – is strict and emission reduction should be reached within the electricity sector, different dynamics will be found. Emission rights will be limited and the only alternative to achieving reduction by investment is paying the penalty. One can have strong arguments for both settings; which is point for discussion in a later paper. For now, we started out with the phase II rules; we plan to do simulations with a hard cap on the sector in the near future.

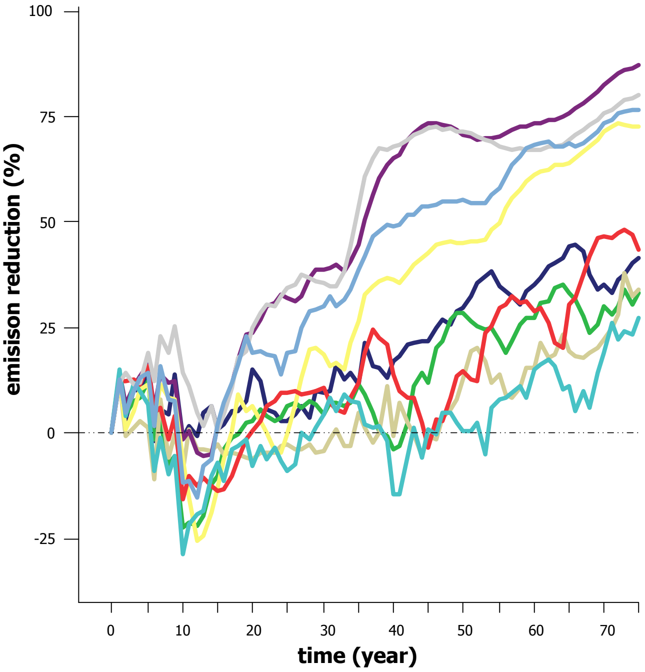

Figure 6. The average impact of CO_2 emission-trading on emissions in different scenarios

5. Simulation results

Some 900 simulations runs have been executed over the extensive scenario-space described above, each with for a time period of 75 years. Initial conditions for all simulation runs are equal, but both the modelled variation in scenarios and stochastic parameters in the model lead to variation in the output.

In order to compare CET with 'no-intervention, for both cases the same number of simulation runs have been completed. This is key in interpreting and assessing the relevance of the results: these simulation outcomes are compared; the focus is not on interpretations of the absolute numbers. Rather, the simulation results for emission trading and no intervention are statistically analyzed and aggregated to enable interpretation of the results and comparison of these two cases.

The impact of CO_2 emission-trading on emissions is shown in Figure 6. Depicted is the emission reduction over time that is the direct 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 had not been implemented, the emissions by electric power generation would on average be 25% higher for scenario *x*. Each deviation from 0% is thus a consequence 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 twenty years, a significant reduction is reached in most scenarios. Reductions can reach even 80% on the long term. Please note however that these are reductions compared to no intervention. The absolute emissions still rise under most scenarios, because total electricity demand rises.

In Figure 7 the composition of the electricity generation portfolio over time is displayed. Again, this a statistical average over all scenarios and runs; implicitly, 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 drawn in a system where emission-trading is absent: in dotted lines and faded colours. An impact of CET is clearly discernable: the development of the composition of the electric power generation portfolio differs. In the first decades the impact is minimal: current standing installations are not replaced until their technical 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, coal is quite dominant in both policy settings. The *relative* amount of coal does decrease under emission trading though, as it starts at a 45% share and ends at a 30% share. However, coal is not banned.

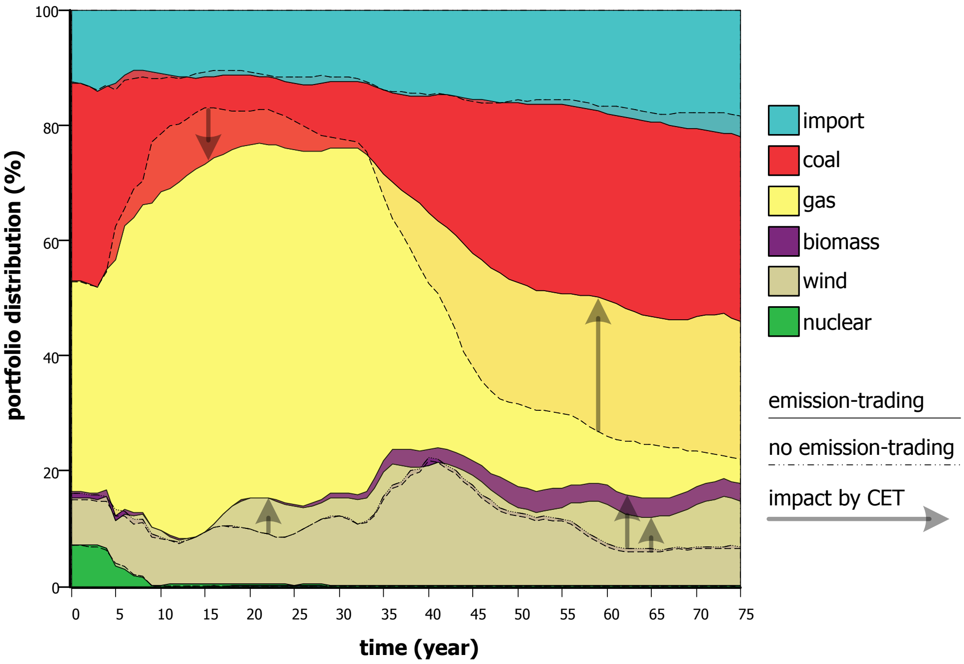

Figure 7. The average impact of CO_2 emission-trading on developments in portfolio composition

Note that clean coal technology is not displayed: it is not adopted in significant amounts. That is caused by the assumption of high variable cost for transport and storage of CO_2 and the higher investment cost for the capture technology and connection to a suitable infrastructure (see Table 2). The shift to coal is therefore not a shift to coal with capture and storage, but rather a shift to conventional coal. Although we see this shift, it would be far stronger without emission-trading, in other words, it is partially prevented by emission-trading. Without any carbon policy, coal appears to dominate the energy sources for power generation. Emission trading leads to increased use of both renewable sources in the model, but power producers withhold to adopt them in dramatic amounts.

Given a dramatic increase in demand and assuming that rights are available in other sectors and countries, conventional coal is necessary in the portfolio and still competes with the other energy sources: it is even a relatively attractive option for power producers. At reasonable CO_2 prices, it has low variable cost (especially fuel cost) and therefore is part of base load: capital utilization is relatively high. Since electricity prices rise, power producers still make a profit.

Under these assumptions, the effect of emission trading is thus not strong enough for power generation to reduce actual emission levels. Although more realistic assumptions would change this result, the findings are insightful: the effectiveness of this policy is strongly dependent on technology and economy. Cost levels for CCS technology, learning curves and decrease in demand are crucial for its success and those three are not directly impacted by the policy itself!

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 8 show that the portfolios of the agents develop differently – note that on average they possess equal initial portfolios. It was found that electricity producer 3 had the highest power generation capacity at all times and was also most profitable. Since in the model this producer is also the largest emitter– it uses the most coal of all agents and only little amounts of renewable sources – and the most profitable (!) it appears it continues to pay to burn coal. Apparently emission trading does not generate a sufficiently strong price-signal to induce a total shift, especially since in reality the management style and associated decision criteria might change over time towards the criteria of the more successful power producers.

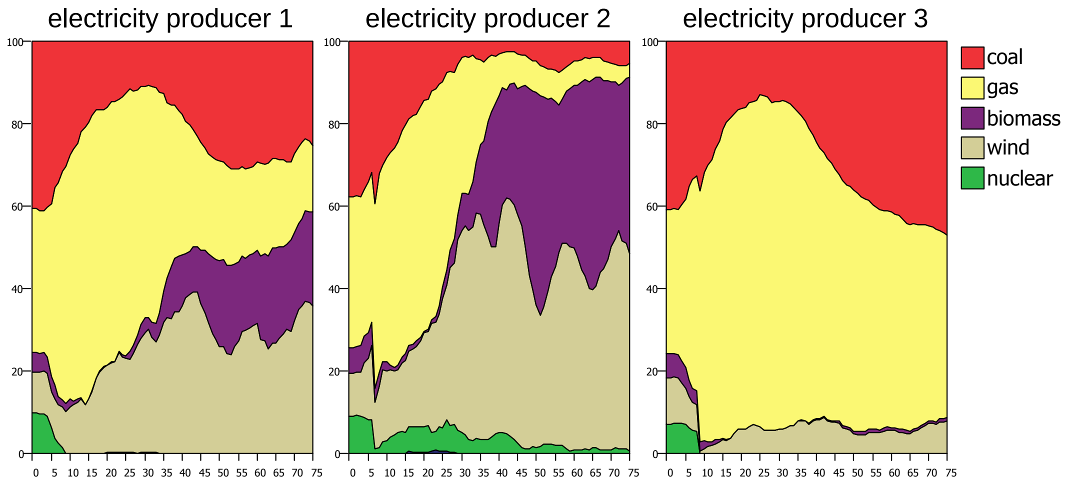

Figure 8. Portfolio developments of individual electric power producers.

6. Conclusions and implications

In comparison with no intervention, the impact of emission trading on CO_2 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 conventional coal is still adopted: driven by low coal costs and an increase in electricity demand, coal use appears to be unavoidable. The share of coal is found to be more in balance with the other energy sources under CET.

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. Although those are reasons why the adoption levels of coal might be lower in reality, coal is attractive for its flexibility: using coal technology, one can co-fire biomass and one has option to capture and store the CO_2 later.

Interestingly, 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, presented per fuel type. For some coal power plants planned for the Netherlands it is possible to co-fire biomass with the coal. The biomass figures are calculated with a maximum of 15% co-fired, on basis of energy content. 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. With a 46-52% share of total capacity planned, coal probably exceeds the natural gas capacity planned. In Germany this is even worse: 68% of capacity expansion is planned to be coal-fired power plants. This equals 30 GW_e which corresponds to 1½ times the presently installed Dutch power generation capacity. Also in the UK, the first coal power plant in 20 years is planned to be built after 2010 [32]. It seems surprising that even after the introduction of CET current power generation capacity expansion plans indicate a preference for coal. Coal has even more advantages than was reflected in the models. 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.

The next step is a model with a strict cap, which is reduced by 1.7% each year, and where rights are not grandfathered but to be acquired by auctioning. This reflects the current thoughts of the European Union on the post-2013 ETS. In such a model, the power generation sector is expected to incur much larger costs for the emission-rights. The amount available gets smaller each year. Additional further research is to compare CET as per ETS phase I and II (this paper) and post-2013 with a system of carbon taxation and other carbon policy types. A model incorporating endogenous or exogenous learning curves is on the research agenda as well and might give more concrete insight in developments of the power generation portfolio. In addition, the other industries under ETS might be explicitly addressed in a future model.

Table 4. Plans for new power plants in the Netherlands and Germany, calculations based on public sources [33; 34]

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*		

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