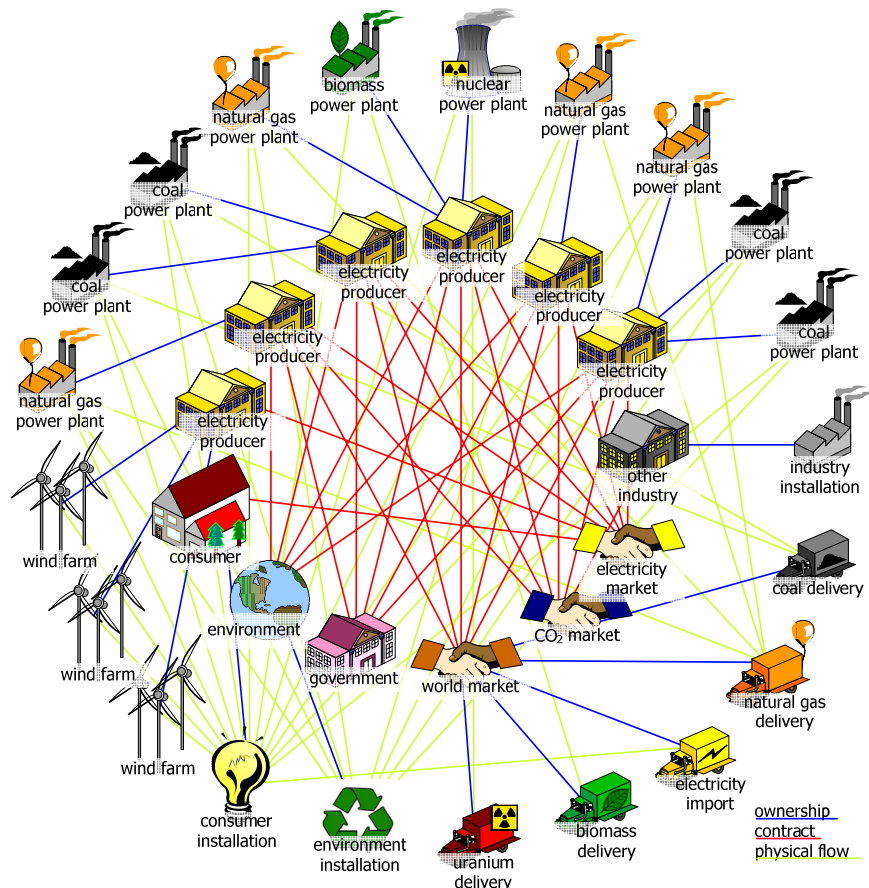


# Carbon Dioxide Emission Trade Impact on Power Generation Portfolio

*Agent-based Modelling to Elucidate Influences of Emission Trading  
on Investments in Dutch Electricity Generation*





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*Keywords:* CO<sub>2</sub> emission trading; power generation portfolio; agent-based model

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# Preface

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This document is the main product of the research done in the last stage of my MSc education in Systems Engineering, Policy Analysis and Management at Delft University of Technology.

A CD-ROM is included as last appendix of this report that contains the model developed during this project.

I wish to thank all around me, for joining me in this exciting and insecure process. I would like to thank my supervisors Gerard Dijkema, Rolf Künneke, Margot Weijnen and Peter Vogtländer for the professional and constructive guidance and for all the opportunities. My thanks are also due to my colleagues Michiel, Koen and Igor for all the collaborative support and for our inspiring meetings and travels. Next, I owe a special debt of gratitude to Paul for his friendship, for the inspiring discussions and for 'our' music. Furthermore, I am very grateful to the tireless willingness of Marlene to review this document. In addition, I owe much gratitude to my family Wilma, René, Cyril, Maryse, Marcel, Mirjam, Sophie, Jos and Ine for the unconditional support, freedom, trust and the love. Finally, I wish to thank Geertje, for her understanding, her inspiring creativity and optimism, her humour and for our love that grows every day, far beyond anything that can be measured or understood by any research.

Emile Chappin, 14 November, 2006.



*The beauty of nature arises out of self-creation, which requires freedom from non-natural influence*  
(Eugene Hargrove, 1989)





# Abstract

---

As of January 1st, 2005 CO<sub>2</sub> emission trading (CET) is implemented in the EU as a measure to reduce CO<sub>2</sub> emissions to counter climate change. It requires that any company that exploits certain activities, such as electricity generation must acquire emission rights to account for its production of CO<sub>2</sub>. Within the EU and participating Member States the total amount of emission rights is capped.

Meanwhile the trend of continuous increase of electricity demand is expected to continue. Since the operational flexibility of power plants is limited, only a limited reduction of CO<sub>2</sub> emission can be achieved in existing installations. A more dramatic effect can be expected from proper selection of CO<sub>2</sub>-light or CO<sub>2</sub>-free modes of electricity generation.

In a liberalized market, investment decisions on electricity generation capacity are made by individual companies who have incomplete and imperfect information. There is no central coordination. CET does provide an economic incentive to shift decision-making and thereby shift the total electricity generation portfolio. However, the long-term impact of CET on emissions by electricity generation is unknown. The objective of this research is to obtain insight into the long-term effects of CET on the electricity generation portfolio by means of a simulation model.

The main question for the research is: *How can the effect of CO<sub>2</sub> emission trading (CET) on the CO<sub>2</sub> emissions, caused by a change in the composition of the Dutch electricity generation portfolio, be elucidated with a simulation model?*

CET imposes an additional type of costs, called CO<sub>2</sub> costs, on electricity generation, next to investment, fuel and other operational costs. To an electricity producer CO<sub>2</sub> costs influence the attractiveness of energy sources, because they differ in CO<sub>2</sub> intensity – the emission per unit electricity produced. CET therefore is expected to affect investment decisions in generation capacity. As a consequence, over time CET could change the electricity generation portfolio. However, this shift is a slow process because electricity generation is capital-intensive and the installations have a long lifespan.

Agent-based modelling has been chosen as modelling paradigm to assess the impact of CET on electricity generation. In that paradigm, decision rules of autonomous *agents* are the central object of study. The actual impact of CET on the development of electricity generation portfolio is a consequence of the investment and disinvestment decisions of individual and autonomous electricity producers. Therefore, the paradigm matches this problem.

A set of software tools form an agent-based simulation environment that is used in the Energy and Industry Group. A formalized structure of concepts defines the agents and technological installations and is the language for communication and interaction between agents. Four branches of concepts are distinguished. Nodes are points in a network, such as agents and technological installations. Edges are connections between nodes, such as contracts and flows. Data are properties of nodes and edges. Knowledge contains data on the operation of technological installations.

In the model, electricity producers, government, a consumer, the environment, industry, an electricity market, a CO<sub>2</sub> market and a world market are represented as agents. The backbone of the agent-based model is the list of *potential* actions for each agent. First, electricity-producing agents trade electricity. Subsequently, they acquire the resources needed for the contracted supply of electricity. Third, CO<sub>2</sub> rights are acquired. Finally, agents make investment and disinvestment decisions. In addition, the agents have

control over the installations they own. Electricity producers decide based on individual management styles and market positions. Agents are influenced by exogenous factors, which have been combined in scenarios. The main exogenous factors are fuel prices, electricity demand, the set of available generation technologies and CO<sub>2</sub> emission rights allocated to the electricity sector (cap). System level properties, such as the electricity generation portfolio and electricity prices, evolve because of all individual actions.

The main assumptions underlying the model are exogenous demand for electricity, an electricity market with perfect competition, a homogeneous and transparent world market for fuels, the absence of technological innovation and a static number of electricity producers.

Based on simulation runs over a range of scenarios it is concluded that CET leads to large but late reduction in CO<sub>2</sub> emission. In the simulations it was found that at the end of the simulation period, emissions under CET are 25-80% lower than when CET is absent. In contrast, in the first twenty years, emission reductions were absent. That impact of CET is caused by a shift from CO<sub>2</sub> intensive coal power plants towards less CO<sub>2</sub> intensive power plants. However, the shift occurs with a delay of 30-50 years. In most scenarios, because of the shift, natural gas power plants, wind farms and biomass power plants replace 50% of the coal power plants. The impact of CET in reality is expected to be even larger than assumed in the model. The impact in the first decades will probably be larger, because of the operational flexibility of some of the generation technologies. In addition, electricity producers have the possibility to invest in small units that can be operational at shorter notice than modelled. In the longer term the impact of CET may be larger because of the price elasticity of electricity demand and because of efficiency improvements and innovative technologies.

Although the simulation results indicate that CET leads to emission reduction compared to non-intervention, it is not likely that the emissions are reduced to or below the cap. The main cause is increase of electricity demand. When demand rises, achieving emission reductions to the cap gets increasingly difficult. In the simulations, the emissions by electricity generation are only reduced to its cap under the scenarios in which the impact of CET is lowest of all circumstances and reductions would be achieved without CET as well. In the longer term, significant emission reductions can only be achieved by lower electricity demand or technological innovation. Since CET has no direct effect on innovative behaviour, electricity demand is relatively inelastic to changes in price in reality as well as in the model and CET does not affect price elasticity of electricity demand, it appears that CET does not sufficiently reduce emissions of electricity generation.

Several side effects of CET are observed that indicate costs unnecessary to the reduction. First, under CET, the adequacy of generation capacity is less, because disinvestment occurs more often. That effect is overestimated in the model, but could be significant in reality as well. Second, as a consequence of a decreased adequacy of generation capacity, higher electricity prices are found under CET. Those higher electricity prices may lead to higher profits of electricity producers. It is debatable whether the redistribution of financial means from consumers to electricity producers because of CET can be justified. Finally, when CET is absent, portfolio shifts are faster, because of inadequate price signals for CO<sub>2</sub> emission rights. In reality, electricity producers probably adapt faster.

It is observed that the effectiveness of the impact of CET depends on the set of strategies adopted by players on the market. Although resulting in large emission costs, the optimal strategy may lead to larger emissions. In reality, differences between electricity producers are probably larger than modelled, for instance because of their financial positions. In addition, new entrants can have other strategies and current market players can adapt their strategies. The effect of these aspects requires model expansion and further research.

Additional research is recommended to find improvements for the design of CET in order to increase its effectiveness. In addition, the agent-based modelling environment should be further developed. A user-friendly and robust agent-based software package will lower the burden to use agent-based approaches. In addition, integration with system dynamics would increase possibilities for combining bottom-up and top-down modelling. Finally, tools should be developed for addressing the validity of agent-based models.

## Samenvatting

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In de Europese Unie is CO<sub>2</sub> emissiehandel (CET) vanaf 2005 geïmplementeerd als beleidsinstrument om CO<sub>2</sub> emissies effectief terug te dringen en klimaatverandering tegen te gaan. Een bedrijf met bepaalde activiteiten, waaronder de productie van elektriciteit, dient voldoende rechten te verkrijgen voor zijn productie. De overheid beperkt het totale aantal rechten (de cap).

Ondertussen wordt verwacht dat de elektriciteitsvraag blijft groeien. Omdat de operationele flexibiliteit van installaties beperkt is, is de haalbare CO<sub>2</sub> emissiereductie met de huidige installaties beperkt. Een groter effect kan worden verwacht van de juiste selectie van elektriciteitsproductie met lagere CO<sub>2</sub> intensiteit.

Investeringsbeslissingen worden in een geliberaliseerde markt gemaakt door individuele bedrijven maken investeringsbeslissingen, gebaseerd op imperfecte informatie over de beslissingen van andere marktpartijen. CET introduceert een economische prikkel tot verandering van de besluitvorming en, als gevolg daarvan, een verschuiving in het portfolio van elektriciteitsopwekkingcapaciteit. Echter, de lange termijn impact van CET op de emissies als gevolg van elektriciteitsopwekking is onbekend. Het doel van dit onderzoek is om door middel van een simulatiemodel inzicht te verkrijgen in de lange termijn effecten van CET op het portfolio van elektriciteitsopwekkingcapaciteit.

De centrale onderzoeksvraag is: *Hoe kan het effect van CO<sub>2</sub> emissiehandel (CET) op de CO<sub>2</sub> emissies, als gevolg van een verandering in de samenstelling van het Nederlandse portfolio van elektriciteitsopwekkingcapaciteit worden verhelderd met een simulatiemodel?*

CET zorgt voor een nieuwe kostensoort voor elektriciteitsproductie, naast de bestaande investeringskosten, brandstofkosten en andere operationele kosten. Deze CO<sub>2</sub> kosten beïnvloeden de aantrekkelijkheid voor elektriciteitsproducenten van verschillende energiebronnen, vanwege de verschillen in de CO<sub>2</sub> intensiteit – de CO<sub>2</sub> emissie per geproduceerde hoeveelheid elektriciteit. Daardoor kan de ontwikkeling van het portfolio van elektriciteitsopwekkingcapaciteit door CET veranderen. Verschuiving daarin is echter een langzaam proces, vanwege de lange levensduur van installaties en de omdat elektriciteitsopwekking kapitaalintensief is.

Agent gebaseerd modelleren is gekozen om de impact van CET op elektriciteitsopwekking vast te stellen. In dat paradigma staan de beslisregels van autonome *agents* centraal. Het effect van CET op de ontwikkeling van het portfolio van elektriciteitsopwekkingcapaciteit is het gevolg van investeringen en disinvesteringen van individuele en autonome elektriciteitsproducenten. Daarom is dit paradigma geschikt.

De gebruikte agent gebaseerde simulatieomgeving wordt gevormd door een set van softwarepakketten, gebruikt in de Sectie Energie en Industrie. Een geformaliseerde structuur van concepten definieert de agents en technologische installaties en vormt de taal van de agents. Vier takken van concepten zijn onderscheiden. 'Nodes' zijn punten in een netwerk, zoals agents en technologische installaties. 'Edges' zijn connecties tussen de nodes, zoals contracten en stromen goederen. 'Data' zijn de eigenschappen van nodes en edges. 'Knowledge' bestaat uit data over het opereren van technologische installaties.

In het model zijn elektriciteitsproducenten, de overheid, een consument, het milieu, de industrie, een elektriciteitsmarkt, een CO<sub>2</sub> markt en een wereldmarkt gerepresenteerd als agents. De ruggengraat van het model is een lijst van *potentiële acties* van agents. Ten eerste kunnen elektriciteitsproducerende agents

handelen in elektriciteit. Daarna, verkrijgen ze de benodigde grondstoffen voor de gecontracteerde levering van elektriciteit. Ten derde worden CO<sub>2</sub> verkregen. Als laatste kunnen agents investeren en desinvesteren. Naast deze acties opereren de agents hun technologische installaties. Elektriciteitsproducenten maken hun beslissingen op basis van individuele managementstijlen en marktposities. Agents worden beïnvloed door exogene factors, gemodelleerd in scenario's. The belangrijkste exogene factoren zijn brandstofprijzen, de elektriciteitsvraag, de set van opwekkingstechnologieën en de beperking op hoeveelheid emissierechten voor de elektriciteitssector. Systeemparemeters, zoals prijzen voor elektriciteit en het portfolio van elektriciteitsopwekkingcapaciteit evolueren als gevolg van alle individuele acties.

De belangrijkste aannames achter het model zijn exogene elektriciteitsvraag, een elektriciteitsmarkt met perfecte competitie, een transparante wereldmarkt voor grondstoffen, de afwezigheid van technologische innovaties en een vast aantal elektriciteitsproducenten.

Gebaseerd op simulatieruns van een set scenario's is geconcludeerd dat CET leidt tot grote maar late reducties in emissies. Uit simulaties kwam een reductie van 25-80% aan het einde van de simulatieperiode door CET. Echter, gedurende de eerste twintig jaar zijn de reducties afwezig. De emissiereductie is in de simulaties veroorzaakt door een met 30-50 jaar vertraagde verschuiving van de CO<sub>2</sub> intensieve kolencentrales naar centrales met een lagere CO<sub>2</sub> intensiviteit. Door deze verschuiving, wordt 50% van de kolengebaseerde capaciteit kolen vervangen door aardgascentrales, windparken en biomassacentrales. Het is verwacht dat de impact van CET in werkelijkheid nog groter is dan aangenomen in het model. Het effect zal in de eerste decennia groter zijn dan gesimuleerd, vanwege operationele flexibiliteit van een aantal van de huidige elektriciteitscentrales. Daarnaast bestaat in werkelijkheid de mogelijkheid om in kleine opwekkingsinstallaties te investeren die sneller operationeel kunnen zijn. De lange termijnimpact is waarschijnlijk groter dan gesimuleerd vanwege prijselasticiteit van de elektriciteitsvraag en door efficiencyverbeteringen en innovatieve opwekkingstechnologieën. Daarom is geconcludeerd dat CET leidt tot grote emissiereducties door middel van een verschuiving in het portfolio van opwekkingcapaciteit.

Ondanks dat de simulatieresultaten erop wijzen dat CET leidt tot emissiereducties ten opzichte van geen interventie, is het niet waarschijnlijk dat de emissies worden gereduceerd tot of onder de cap voor de elektriciteitssector. De belangrijkste oorzaak is een stijging in de elektriciteitsvraag. Door deze stijging wordt het steeds moeilijker om emissiereducties tot binnen de opgelegde cap te behalen. In de simulaties wordt de emissiereductie door elektriciteitsopwekking alleen behaald onder scenario's waarin de impact van CET minimaal is en de reducties ook zonder CET zouden worden behaald. Op de lange termijn, kunnen significante emissiereducties boven op de gesimuleerde reducties alleen worden behaald door lagere elektriciteitsvraag en technologische innovatie. Echter, CET heeft geen directe invloed op de innovatie van elektriciteitsproducenten. Daarnaast is de vraag naar elektriciteit in werkelijkheid relatief inelastisch voor veranderingen in prijs, net zoals gemodelleerd en is er geen invloed van CET op die elasticiteit. Daarom wordt niet verwacht dat CET voldoet voor het reduceren van emissies door elektriciteitsopwekking.

In simulaties zijn verschillende bijeffecten van CET waargenomen die indicaties zijn van kosten onnodig voor emissiereducties. Ten eerste zijn er onder CET meer disinvesteringen en is de reservecapaciteit lager. Dat effect is in het model overschat, maar zou in werkelijkheid wel kunnen optreden. Ten tweede, als gevolg van lagere voorzieningszekerheid, kunnen elektriciteitsprijzen stijgen door CET. Daarmee kunnen ook de winsten van elektriciteitsproducenten stijgen. Het is betwistbaar of herverdeling van financiële middelen van consumenten naar elektriciteitsproducenten door de implementatie van CET kan worden gerechtvaardigd. Als laatste zijn portfolioverschuivingen langzamer bij CET, vanwege ontoereikende prijssignalen voor CO<sub>2</sub> rechten. In werkelijkheid, kunnen elektriciteitsproducenten waarschijnlijk beter omgaan met die onduidelijkheid dan in het model.

Het is bevonden dat de effectiviteit van de impact van CET afhangt van de set van strategieën van marktpelers. In de simulaties leidt de optimale strategie tot hoge emissies, ondanks aanzienlijke emissiekosten. In werkelijkheid zijn de verschillen tussen elektriciteitsproducenten waarschijnlijk groter dan gemodelleerd, bijvoorbeeld door verschillen in financiële positie. Daarnaast kunnen nieuwe

marktspelers nieuwe strategieën hebben en kunnen huidige marktspelers hun strategieën aanpassen. Inzicht in het effect van deze aspecten vereist uitbreiding van het model en meer onderzoek.

Aanvullend onderzoek is aanbevolen om verbeteringen te vinden voor het ontwerp van CET, zodat de effectiviteit wordt vergroot. Daarnaast, is het aanbevolen om de agent gebaseerde simulatieomgeving verder te ontwikkelen. Een gebruiksvriendelijk en robuust agent gebaseerd softwarepakket verlaagt de drempel voor een agent gebaseerde aanpak. Daarnaast, verhoogt de integratie met system dynamics de mogelijkheden voor de combinatie van bottom-up en top-down modelleren. Tenslotte, wordt het aanbevolen om technieken te ontwikkelen die de validiteit van agent gebaseerd modellen kunnen bepalen.



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# **Part I. Problem exploration and research framework**



# 1 Introduction

## 1.1 Background

Human kind is using natural resources to fulfil their needs. For instance, fresh water is used for to produce food and other goods, metals are used for the production of goods and buildings, coal is used for the generation of electricity, natural gas is used for electricity production and space heating and oil is used for transport fuels and the production of plastics. The use of resources is however not without impact, since waste heat and substances are emitted to water resources, the soil and the atmosphere. Two main problems are identified with using the resources oil, natural gas and coal.

The first problem is that in the last century, an increase in living standards has caused a dramatic increase in energy demand. Because earth's energy resources are limited, maintaining the production of high quality energy becomes increasingly difficult. The second problem is that the use of oil, natural gas or coal has unwanted side effects. Combustion of these resources contributes to an increase of the greenhouse effect, because of the increased CO<sub>2</sub> emission in the atmosphere. Climate change is the main long-term impact of the greenhouse effect. Policy is implemented to reduce those impacts (see Figure 1).

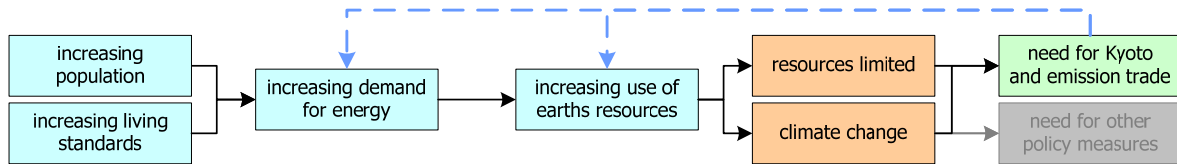


Figure 1. The need for CET.

The increased greenhouse effect is the main cause for temperature rise of the earth's atmosphere. Greenhouse gasses have the property of absorbing a specific portion of the heat radiation released by the earth and reflecting part of the radiated heat back to the earth. The result is a shift in the heat balance of the earth, causing more heat to be kept within the atmosphere resulting in a higher average temperature. The increased greenhouse effect therefore causes climate change, such as temperature rise, more extreme weather conditions, changing water streams, desert expansion and melting icecaps (VROM 2006b). Many governments, scientists and international organizations declare that the effects of climate change are to be prevented and mitigated by taking measures limiting the rise in concentration of greenhouse gasses in the atmosphere (e.g. European Environmental Agency 2006; United States Environmental Protection Agency 2006; VROM 2006a).

If the problem is viewed from a technocratic economic paradigm, the environmental impact of humans is expressed (in a simplified way) by the following formula that was first used by Ehrlich and Holdren (1971; 1972):

$$I = P \times A \times T \quad (1)$$

The environmental impact  $I$  is a product of the population  $P$ , the affluences  $A$ , representing consumption of services and products per capita and the characteristics of the available technology  $T$ , such as the efficiency. Solutions can be found by decreasing each of the three factors  $P$ ,  $A$  and  $T$ . Governments usually mainly address the technology factor, assuming the problems caused by the depletion of resources are technically solvable. In the last decades, environmental policy aims at technological innovation that increases of efficiency and the increase of the use of renewable energy sources.

One of the world-scale policies to reduce the greenhouse effect is the Kyoto agreement. To prevent and counter climate change, many countries agreed to reduce the greenhouse gas carbon dioxide (CO<sub>2</sub>) emissions by ratifying the UN Treaty, generally known as the Kyoto agreement. These countries agreed on a reduction of 6% in the period 2008-2012 below the emission level of CO<sub>2</sub> in 1990. In addition, the EU (and thus The Netherlands) ratified the Kyoto agreement. To be able to reach this goal, countries individually have to provide incentives for companies and consumers to use less CO<sub>2</sub> emitting energy sources.

## 1.2 Overview of CET impacts on electricity production portfolio

CO<sub>2</sub> emission trade (CET) is such a policy measure that can help reducing actual CO<sub>2</sub> emissions. CET has been introduced in the European Union. In such a system, a party has to own a right to be allowed to emit a specific amount of CO<sub>2</sub>. This holds for only a limited set of activities, including the production of electricity. From January 1, 2005, if a company wants to participate in one of these activities it has to acquire the right to emit the CO<sub>2</sub> produced during the exploitation of that activity. This company must report actual emissions as well as the ownership of emission rights to a governmental agency. A fee has to be paid if the company does not own enough permits to cover its emissions. Some of these rights are supplied by the government at no cost. Private companies can trade these rights through a dedicated CO<sub>2</sub> market if they want to. By means of limiting the total amount of permits that can be bought, the actual reduction can be enforced. The main argument used to introduce CET is that it reduces emissions at the lowest costs possible (Svendsen 1999).

In the Netherlands, electricity production represents half of the emissions involved in CET (Cozijnsen 2005). For emissions by several other types of industrial installations, of which the main are refineries and chemical and metal industries, it is also necessary to own CO<sub>2</sub> emission permits. If parties do not get enough permits from the government, CET introduces a new type of costs in the production of electricity, in addition to the investment costs, fuel costs and other operational costs. Additionally, CET imposes opportunity costs for the rights parties get from the government, because revenue can be generated by avoiding emissions and selling emission rights. However, the new expenses imposed by CET come only from the rights that have to be bought on an emission market. Actual emissions of an electricity producer depend on the type of technological installations that are used to produce electricity: the '*generation portfolio*'. For instance, a wind farm does not produce any CO<sub>2</sub>. In contrast, a coal-fired power plant produces a lot of CO<sub>2</sub>. With CET, the relative profitability of the different alternatives for the production of electricity depends on the costs for CO<sub>2</sub> rights. A shift in power plant types, or generation portfolio, can be expected as a consequence of the impact on the investment decisions of electricity producers. This portfolio shift in turn has an influence on the demand for CO<sub>2</sub> rights. Electricity production and CET therefore are interdependent. Figure 2 shows this interdependency.

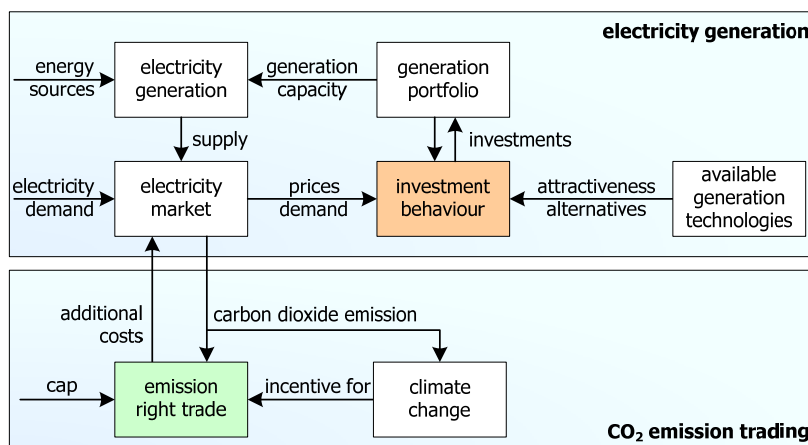


Figure 2. Relations between the electricity sector and CO<sub>2</sub> emission trading.

The electricity sector was recently restructured. Throughout Europe, the electricity sector is in a privatisation and liberalisation process. Regulation forces electricity firms to split up in the Netherlands,



creating competitive markets for electricity production, trade, delivery, import and export and metering respectively. Dutch regulation separates commercial activities from network management. In the liberalised electricity sector, investments in electricity generation are not centrally planned. Market players invest autonomously, without top-down control by government. Investment decisions are taken by distributed actors with imperfect information of the plans and decisions of other parties. The composition of the electricity generation portfolio and the actual CO<sub>2</sub> emissions are emerging system level consequences of these lower scale decisions.

In chapter 2, CET impacts on electricity generation are explored in more detail. That discussion encompasses a discussion of the actors involved. Next, a discussion is presented on the design issues for CET, namely the target group, the allocation of emission rights, enforcement, trade over time periods and level playing field. The choices made on European and Dutch scale are stated. In addition, technical and economic aspects of electricity generation are presented. Finally, a discussion of the impacts of CET on operational and investment decisions by electricity producers is given. Based on that exploration, the problem statement in the next paragraph is derived.

### 1.3 Problem statement

The contribution to be expected of CET on emission reductions in the electricity generation sector is unknown. CET has been implemented under the economic assumption that it is effective in reducing actual CO<sub>2</sub> emissions. However, the impact of CET on investments in electricity generation facilities is unknown.

In the implemented CET system, government caps the amount of emission rights. If CET is assumed not to affect the demand for electricity (the demand is exogenous to CET), emission reductions within the sector must be caused by a shift in power plant *technology type*. In other words, CET should result in a shift in the electricity generation portfolio.

The extent of the shift in generation portfolio that can be expected over time is unknown. However, it is mainly determined by two factors. First, the lifespan of power plants (typically decades) greatly affects and delays a portfolio shift. Second, as was mentioned above, central coordination or planning is absent. Instead, the portfolio emerges from distributed investment decisions. In the liberalised electricity sector, electricity producers decide individually upon investments, using their own criteria. As a consequence, the long-term effects of CET on emissions from electricity production are unknown and uncertain; insight is desirable. Insight into the impact of CET on the mix of electricity power plant types can only be acquired by simulation models that incorporate technical as well as economic aspects of this problem. Such a model does not exist.

### 1.4 Research goal, questions and problem owner

The main objective is to obtain insight into the long-term effects of CET on the electricity generation portfolio by means of a simulation model.

The **main question** for the research is:

*How can the effect of CO<sub>2</sub> emission trading (CET) on the CO<sub>2</sub> emissions, caused by a change in the composition of the Dutch electricity generation portfolio, be elucidated with a simulation model?*

The following research questions will lead to answering the main question.

1. What is CET?
2. With what criteria can the effect be assessed of CET on the development of the Dutch electricity generation portfolio?
3. What modelling paradigm is preferred to simulate CET and the evolution of the electricity generation portfolio?
4. Using the preferred modelling paradigm, what must be included in the simulation?
5. How can a prototype model best be implemented?

6. Based on the assessment criteria applied and the simulation outcomes, what claims can be supported on the effectiveness of CET?

Due to the fact that emission reductions are urgent and the introduction of CET should contribute to these reductions, this research has a high societal relevance. It is often claimed that CET leads to cost effective emission reductions (Svendsen 1999). On average in Europe, the electricity sector produces one third of the amount of emitted CO<sub>2</sub> included in the CET (Svendsen *et al.* 2003). In the Netherlands, half of the CO<sub>2</sub> emissions are caused by electricity production (Cozijnsen 2005). Society depends on electricity for the most part of its activities. Since there is a lack of experience with CET on this scale, literature on this subject is also scarce, especially literature with the focus of this research, namely the impact of CET on the development of the electricity generation portfolio. That impact is uncertain and therefore needs elucidation.

The main problem owner is the Dutch government. For this problem, the main relevant bodies of the Dutch government are the Ministry of Housing, Spatial Planning and the Environment (VROM) and the Ministry of Economic Affairs (EZ). VROM is responsible for the implementation of the EU directive that prescribes the setup of CET. In addition, VROM is responsible for climate policy. EZ is responsible for the economic impact that CET has on the sectors involved. In addition to these governmental problem owners, the developed model can also be useful for other actors involved, such as electricity producers. The project is executed for the Energy and Industry Group at the faculty Technology, Policy and Management at Delft University of Technology.

## 1.5 Scope and outcomes

### Research scope

The focus of this research is on the effects of CET on investments in electricity generation. CET on the long term imposes a change in the development of the generation portfolio by specific technology selection. In other words: changes in the amount to which possible types of power plants are used. Second, the focus is on the Dutch situation as far as it is specific. This can be done because electricity is essentially a regional commodity: inter-connector capacity between the Netherlands and neighbouring countries is relatively low and it is not expected to increase dramatically. Moreover, electricity transport losses over long distances are significant.

Within this scope, it cannot be expected that a complete and finished answer is given to the research question. This research is of an explorative nature, because of the complexity of the system and the limited literature that is available on the focus used in this thesis.

### Model scope

In view of the fact that this research is the first attempt to model the long-term impacts of CET on electricity generation, additional assumptions were made to be able to develop the model. Those assumptions include the absence of technological developments (e.g. no efficiency improvements or changing costs for investments). In addition, regulation is static (e.g. no governmental intervention). Furthermore, producers do not merge, enter or exit the generation part of the electricity sector and that the market strives for adequacy of generation capacity. The setup of the model is such that all these assumptions can be tackled in the future, for instance the modelling of merging companies.

The study is designed to balance the following two goals for the model: The first goal is that the model should give as much insight as possible into the actual impact of CET on the development of the Dutch electricity generation portfolio composition. The second goal is that the model should be flexible enough to be useful after this thesis project for further development.

### Outcomes

The main outcome of this research is insight in the actual impacts of CET on emission reductions and portfolio shifts in Dutch electricity generation under different scenarios. In addition, actors involved in CET and electricity generation can use the model as decision support tool, in spite of the assumptions

underlying this model. Besides that result, a contribution to the development of the used modelling environment is made.

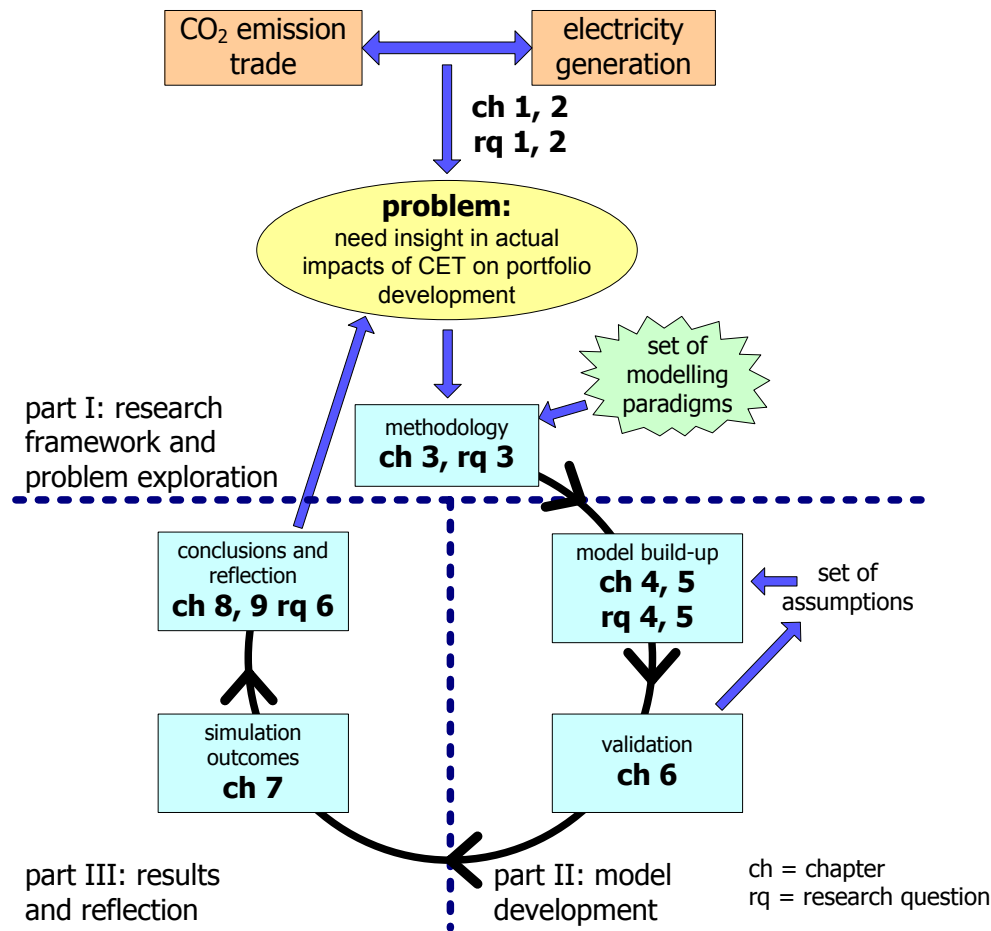


Figure 3. Structure of this thesis.

## 1.6 Structure of this thesis

The thesis is build-up of three parts (Figure 3). Part I gives a thorough background on the problem and a discussion of the modelling approach. Part II presents the model that follows this approach. Part III presents the results of simulation runs of the model and reflects on the approach and the modelling choices.

The first part, subsequently to this introductory chapter, gives an analysis of the current state of literature on CET and relevant economic and technical aspects of investments in electricity generation portfolio. From this discussion, a set of assessment criteria for CET impacts are derived that are tested with the model built in the second part. Chapter three discusses the steps that were taken in the research process and which methods were used to structure that process. After a comparison of the main modelling paradigms, the choice for agent-based modelling as modelling paradigm is justified.

The second part details on the development of the model. The model description of Chapter four basically is a thorough overview of the models' main components together with a discussion of the assumptions for which the model holds. Chapter five contains the main remarks on the implementation of this model, to show how the model was fit in the existing ABM environment of the Energy and Industry Group. Chapter six discusses the validity and limits of the model. It mainly reflects on the modelling assumptions discussed in the fourth chapter.

The third part consists of a discussion and reflection of the results of this thesis. First, the simulation outcomes of the model are presented. Conclusions from these results are drawn in Chapter eight to provide an overview of the score on the criteria presented in the first part. Reflection on these results with respect to the chosen approach and an outlook to future work is also presented in that chapter. Finally, Chapter nine reflects on the model development process of this thesis.

## 2 Problem exploration

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### 2.1 Introduction

This thesis is about the long-term impacts of CO<sub>2</sub> emission trading (CET) on the development of the electricity generation portfolio. In addition, criteria are derived to assess those impacts. This exploration is needed to select the preferred modelling paradigm. In the second part of this thesis a model is presented that is built in the chosen paradigm. The impacts of CET on electricity generation are assessed with that model.

First, CET is introduced. After that, an overview of the main involved actors is given by performing a multi-actor analysis. That overview is used in the rest of this chapter. Next, the design choices in the European and Dutch CET setup is presented. A discussion of the technical and economic aspects of electricity generation follows. These are needed to discuss the operational actions and investment decisions in electricity generation. That discussion is important, because the impact of CET on reductions of CO<sub>2</sub> emissions is by the influence on those investment decisions. Then, the operational impacts of CET on industrial activities in general are discussed with an example to show the functioning of CET. Subsequently, the long-term impacts of CET on electricity generation are described. Finally, the assessment criteria for CET impact on electricity generation are derived. Conclusions mark the end of this chapter.

### 2.2 Introduction to CET

As of January 1st, 2005, CET is implemented in the EU to meet the reduction agreed upon in the Kyoto protocol in a cost-effective way. The general idea of CET is formalized in the EU directive 2003/87/EG: "Member States shall ensure that, from 1 January 2005, no installation undertakes any activity listed in Annex I resulting in emissions of a greenhouse gas specified in relation to that activity unless its operator holds a permit issued by a competent authority in accordance with Articles 5 and 6." Thus, for a specific list of industrial activities, a party that wants to exploit such an activity has to own a permit to emit the CO<sub>2</sub> that is produced by this activity. A company that produces electricity with a process that emits CO<sub>2</sub> has to own CO<sub>2</sub> emission rights for that amount. This company has to show this ownership to a governmental agency. A fee has to be paid if the company does not own enough permits.

The European Commission has selected to use a cap and trade system (Cozijnsen *et al.* 2005). In this system, the total amount of carbon emission rights is fixed and reallocation takes place by trade. For each trade period, an allocation plan is produced by the government, stating how many rights each party can acquire for free. Each trade period, parties acquire that amount of rights and by trade with other parties they can adjust it to their actual need. Markets are expected to emerge in which parties can sell or buy rights for emitting CO<sub>2</sub>. To be certain to reach the reduction, the authorising party limits the total amount of rights, which can even be adjusted over time. Because of the trade, a value is attached to these rights, and a right thus becomes an asset of the owner. In general, it is expected that parties that are willing to pay most for the rights available are the parties that can earn most money by emitting that CO<sub>2</sub>. Consequently, only the most favourable CO<sub>2</sub> emitting activities are exploited. Nations of the EU have implemented CET on a national scale from 1 January 2005. From 1 January 2008, also international trade will be possible. The market price for emission rights is the main driver in CET.

Possibilities exist to acquire more rights than the limit of the cap set by the government. The Kyoto protocol creates flexible opportunities for this purpose, designed to lower the costs of reducing CO<sub>2</sub>

emissions. The general idea is that since the greenhouse effect is global, the locations of the reductions are irrelevant. The Clean Development Mechanism (CDM) is one of the flexible mechanisms. Under the CDM, a country that has a CO<sub>2</sub> reduction target can invest in a specific projects in a developing country without such a target in order to claim credit for the avoided emissions achieved in that project. For example, an industrialised country may invest in a wind power project in a developing country that replaces electricity that would otherwise have been produced from coal. The industrialised country can claim credit for the emissions that have been avoided, and use these credits to meet its own target. For industrialised countries, this greatly reduces the cost of meeting the reduction commitments that they agreed to under the Kyoto Protocol (CDM Watch 2006). A second mechanism is Joint Implementation (JI). Joint Implementation allows parties to implement projects that reduce emissions or remove carbon from the atmosphere in another country with a reduction target, in return for emission reduction units (ERUs). The ERUs generated by JI projects can be used towards meeting their emission targets under the Kyoto protocol (UNFCCC 2006). In addition, government can acquire CDM or JI allowances to bring more rights to the emission market.

### 2.3 Multi-actor analysis

A number of actors are involved in CET and in electricity generation. Based on a multi-actor analysis, a discussion of the actors ‘critical’ to the problem follows. Critical actors are the ones that cannot be replaced. Moreover, they have significant means to influence the problem, stated in the first chapter. Table 1 gives an overview of all the critical actors involved, their main goals and means with respect to CET impacts on electricity generation. Appendix A contains a more elaborate analysis of all actors involved in CET and electricity generation as well as the arguments for selecting these actors as critical.

**Table 1. Overview of critical actors with their goals and means.**

<i>group</i>	<i>actors in group</i>	<i>goals of group</i>	<i>means of group</i>
public interest	European Commission Ministry of Economic Affairs (EZ) Ministry of Housing, Spatial Planning and the Environment (VROM) Dutch emission authority (NEa) end consumers of electricity	maximizing social welfare by countering climate change affordable electricity secured electricity supply	regulation subsidy agenda setting sanctions
private interest	electricity producing companies chemical industry	continuity high profits	market power financial power strategic behaviour

In this overview, two groups of actors are distinguished. The goals and means stated are in reality more nuanced. The first group has the common interest of *social welfare*. They have social goals, such as countering climate change, low electricity prices and a secured electricity supply. The second group of actors has a private interest: these actors strive for continuity and high profits.

The first group contains governmental parties end consumers of electricity. The European Commission installed CET to reduce CO<sub>2</sub> emissions. However, not all design choices are made on the European level. The Ministry of Economic Affairs is responsible for the Dutch design of CET. The Ministry of Housing, Spatial Planning and the Environment is responsible for issues on the environment in general. In the Netherlands, an authority supervises CET. That authority is called the Dutch emission authority (NEa). Different goals and interests are possibly conflicting within the actors of this group. For instance, the goals countering climate change and a secure electricity supply may well be conflicting. If that is the case, trade-offs have to be made in regulation. This trade-off is dynamic and among other things is the result of political debates and decisions. Change in regulation is a great source of uncertainty for the parties involved. The end consumers pay for electricity and have an interest in affordable electricity. At the same time, they benefit from a stable climate.

The second group of actors involves parties with a private interest. Electricity producing companies and a selection of companies in the chemical industry are obliged to participate in CET. Participating is not primarily in their interest, although they may have social goals in addition to their private interest.

This is only a brief introduction on the actors involved. Detailed information can be found in Appendix A and in the remaining part of this chapter.

## 2.4 European and Dutch CET design

This section discusses the design of CET in Europe and in the Netherlands. Within the selection for a cap and trade system, several options exist in the design of CET system. Issues in the design of the greenhouse gas emission market as proposed have not been analysed completely yet. Many effects of CET are unknown, because emission right markets do not yet exist on this scale. Market price ranges for CO<sub>2</sub> rights, actual consequences for the sectors involved and scarcity on the emission right market are uncertain. This section gives for each design parameter an overview of the discussion in scientific literature and discusses the choices made for Dutch CET with regard to that parameter. The main design parameters are defined by Svendsen and Vesterdal (2003): the target group, the method for allocation of emission rights, enforcement and trade over time periods. In addition, the level playing field of the involved countries is addressed.

### Target group

The target group consists of the sectors and the types of installations in those sectors that are obliged to participate in CET. Svendsen and Vesterdal (2003) argue that only the largest emitters should be included and not all emitting parties to decrease the transaction costs of the system, in the form of administrative costs. However, Böhringer *et al.* (2005) argue to include all emitters in CET to reduce allocative inefficiencies. There is a trade off between the administrative costs for the small parties and the governing party and the profit gain for society by including them.

The Dutch Government have chosen that small players (yearly emission smaller than 25 kton CO<sub>2</sub>) may decide to participate in the emission trade system for the first period (2005-2008). Therefore, small players have the possibility to be excluded, also called *opt-out*. There are 164 potential players with this option. Almost 40% of these players deliberately joined the system. They are expected to emit 1.15 Mton CO<sub>2</sub> (SenterNovem 2006). Arguments to participate voluntarily are twofold. First, they may see opportunities to sell part of their rights by profitable changes in their processes. Second, they could feel a responsibility for society and want to cooperate because of that responsibility. As parties that do not participate in CET are obliged to follow all other current policy and regulation, the reductions of emissions are probably reached anyway.

### Allocation

A second design parameter deals with the question how the rights are to be distributed initially among CO<sub>2</sub> emitting parties. Possibilities are auctioning the available amount among interested parties, grandfathering or a combination of these. Auctioning emission rights can generate early price signals (Ehrhart *et al.* 2003). With *grandfathering*, the rights are supplied on a cost-free basis in a scheme based on current and past emission levels. Svendsen and Vesterdal (2003) argue that allocation should be based on a combination of grandfathering and auctions. Historical emission data are to be used in that process (Vesterdal *et al.* 2004). Grandfathering is argued to favour the existing parties by imposing a financial barrier on new entrants (Markussen *et al.* 2005). New entrants have no current or past emissions and therefore they are not able to get any free emission rights when grandfathering is used. The party that can make most profit out of a process per quantity of emitted CO<sub>2</sub> can afford most money for an emission right. Assuming that all the parties have the same access to capital required for those emission rights, auctioning has the advantage that the most CO<sub>2</sub> efficient parties will buy most rights, which is socially beneficial. As a consequence, the least efficient parties will not obtain a right to emit, which is socially the most effective way to reduce CO<sub>2</sub> emissions.

An important question regarding allocation is which property rights existed before the government installed CET. Did industry have the right to emit CO<sub>2</sub>? Did society as a whole (thus each citizen) have the right to live in a world with a stable climate and clean air? Both property rights cannot exist at the same time, they are conflicting. Before installation of CET, it was not explicit which of the two was more important and therefore overruled the other. As a consequence, it is not clear whether it is fair to auction the right to emit CO<sub>2</sub>. By auctioning these rights, money is paid for the right to emit CO<sub>2</sub> that, before

CET was implemented, was implicitly owned by the emitting parties already. By grandfathering these rights, administrative costs are posed on consumers who thought to have the right to a stable climate without costs. In addition to the fact that grandfathering and auctioning have different implications, the choice between them makes overruling property rights explicit. For instance, by choosing for grandfathering, government attaches a value to the right to emit CO<sub>2</sub> – formerly owned by the emitting party – to make that right tradable.

Another grandfathering configuration is that end consumers of a selection of products get an amount of CO<sub>2</sub> emission rights. The consumer has to transfer the rights to the party they purchase such products from. In such a setup, a household would transfer emission rights to the electricity provider they buy electricity from. The reasoning behind this configuration is that electricity is produced for the need of the consumer. In other words, the consumer is the cause of the emission. However, the administrative effort would be high and it needs active participation and understanding of end users.

The Coase theorem says that the property rights are well defined, independent of the one who owns that right (thus the right to emit CO<sub>2</sub> or the right to have a stable climate and air with a stable CO<sub>2</sub> concentration), the rights will be redistributed by bargaining until an efficient distribution is achieved (Coase 1960). In other words, it does not matter which right is chosen to be more important, as long as one is chosen. That only holds under the assumption that transaction costs and bargaining costs are irrelevant. However, these costs are significant. In an ETS administrative costs have to be made, agencies have to be installed to monitor transfers and solve conflicts, market schemes have to be setup and finally, fees have to be paid per transfer. These transaction costs probably differ per allocation setup (discussed above). The costs for setting up auctions might well differ from costs for setting up grandfathering allocation schemes. No conclusions can be drawn based on the Coase theorem, on what configuration can be recommended, because the difference cannot be substantiated by the available literature.

EU regulation limits the choice by determining that the use of auctions is allowed for up to 5% of the available rights for the first period (2005-2008) (Europese Unie 2004). The other rights should be provided freely by some national allocation plan. The choice of the Dutch government is to provide all rights freely and not to use auctioning. The Dutch allocation plan provides a scheme in which the rights are allocated on the basis of the emission levels in the period 2001-2002. Grandfathering is thus used. However, the scheme is also based on the expected sector growth (researched by ECN and RIVM), an energy efficiency grade (that indicates the relative efficiency of a particular installation based on energy covenants) and a correction factor to match the total amount of credits (SenterNovem 2006). New entrants and parties who have made plans already to increase their production before 2008 however, can obtain equivalent rights freely also. Moreover, a part of the emission rights are reserved for new entrants. This means that new entrants have no large disadvantage. However, the system is administratively very intense. Redistribution of the rights will take place through the emission rights market to reach the socially optimal distribution of the rights.

## Enforcement

Another design issue is how to design the registration of actual emissions. Enforcing deals also with sanctioning the absence of required emission rights. The Dutch government regulated that the actual emissions are to be reported by means of an emission report. The emitter itself makes this report and has to arrange verification by a registered verifier. This coincides with Svendsen and Versterdal (2003) who recommend enforcement by self-reporting. It is assumed that cheating is not possible in the measurement of actual emissions, because standard rules apply and measurement of emissions is technically not complicated. A penalty is set in place for parties that do not acquire enough rights. The penalty is 40 €/ton CO<sub>2</sub> in the first period (2005-2007) and 100 €/ton CO<sub>2</sub> in the second period (2008-2012). Additionally, the rights that were missing will be subtracted from the grandfathered rights of next year (Europese Unie 2004). Because of that subtraction, parties emit CO<sub>2</sub> to their needs by paying the fee. After the absence of emission rights in period A, the total amount of grandfathered rights in period B is adjusted such that over both periods, the cap is obtained. This means that parties will not gain by having a shortage of emission rights. The penalty will therefore not function as a price cap in the market.



### Trade over time periods

Schleich *et al.* (2006, page 119) argue for the need for emission trade over time periods: “Admitting banking in emission trading systems reduces overall compliance costs by allowing for inter-temporal flexibility because cost savings can be traded over time”. However, it could also be used strategically. If a party is risk averse, he might want to have some reserve rights. A risk taking party may buy excess amounts of rights, because new scarcity will lead to higher prices if the market functions reasonably perfect. The total amount of emission rights will be reduced over time, creating even more scarcity in later periods and therefore probably higher prices. Speculating on rising prices may not be beneficial to society as a whole. So far the possibility to trade over time periods is not allowed by Dutch regulation (SenterNovem 2006).

### Level playing field

Within the design for CET made on the European level, nations have to make more specific decisions. As a consequence, national CET designs deviate: the subsidiarity principle applies to CET design. Differences between countries become relevant if trade is possible between countries. This can have consequences for the level playing field in Europe, because firms have increased differences in their regulatory surroundings, causing more possibilities for strategic behaviour.

## 2.5 Electricity generation and its portfolio development

Electricity generation is one of the sectors obliged to participate in CET. The focus on electricity generation is because of two reasons. First, electricity generation causes half of the total amount of emissions and is therefore the largest sector (Cozijnsen 2005). Second, electricity is very important in modern society: the access to electricity is one of the first necessities of life. Consequently, the analysis of this thesis focuses on the development of the electricity generation portfolio. This paragraph starts with an introduction to the electricity sector as a whole. After that, a discussion follows on the technical aspects of electricity generation. Subsequently, the economic aspects of electricity generation are addressed. Finally, an overview of the operational and investment decisions in electricity generation is presented.

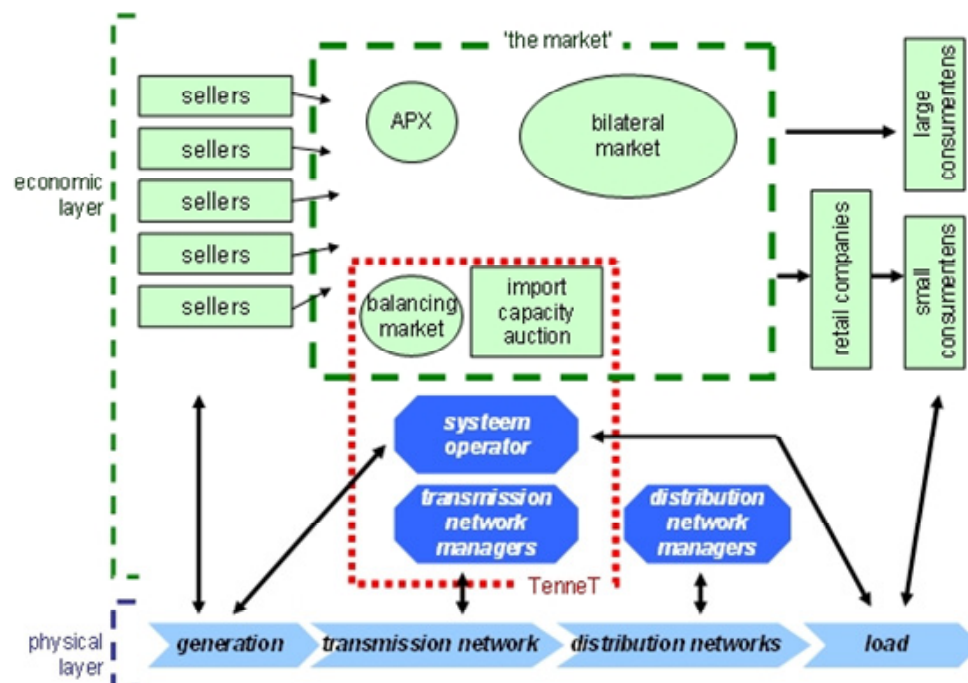


Figure 4. Liberalisation and unbundling of the electricity sector (Vries *et al.* 2004:4).

### Introduction to the electricity sector

This section gives a short introduction to the physical and economic aspects of the Dutch electricity sector. Figure 4 gives an overview of the current Dutch electricity sector. In the last decade, the structure

of the electricity sector throughout Europe has changed. In the Netherlands, a liberalization process forced the different parts of the electricity value chain to be unbundled. Generation of electricity is therefore separated from transmission, distribution and retail. A distinction is made between the physical and economic aspects of the electricity sector (Vries *et al.* 2004).

#### *The physical layer*

Electricity actually flows through physical transmission and distribution networks, distinguished by their voltage level. TenneT, the Dutch transmission system operator, owns the only available Dutch transmission network. The transmission network connects large power plants and distribution networks. The transmission network transports electricity through cables at (very) high voltage. Local governments (municipalities and provinces) own the distribution networks. Distribution networks connect small and large end consumers to the transmission network. Consumers are connected to the lower voltage distribution networks. Also small plants feed in to the distribution network. Large consumers may connect to the transmission network directly.

Electricity cannot be economically stored on large scale. Therefore, the input and withdrawal of electricity to and from the physical network must be balanced at all times. This causes a need for reserve capacity to prevent blackouts during peak demand. Second, it calls for the need of electricity generation capacity that can ramp up and down on very short term, based on actual flows of electricity.

The capacity for importing electricity into The Netherlands is limited by the *inter-connector capacity* between the Netherlands and surrounding countries, which in total is around 20% of the total domestic demand for electricity (NMa 2005). The main exporting countries to The Netherlands are Germany and France. The electricity generally comes from nuclear and coal based power plants, which have lower generation costs than most Dutch power plants. Consequently, inter-connector capacity is fully used to import electricity into the Netherlands. This phenomenon is in this thesis called '*import dominance*'.

#### *The economic layer*

The left side in this figure, the supply side of the electricity sector, consists of electricity generating companies, owning power plants. Based upon the prices that they offer, the processes that occur in the market decide upon the quantity of electricity that each generation company is allowed to sell at each moment in time. The generating companies themselves however decide autonomously in their biddings which plants they run and how they run them.

Producers and consumers of electricity trade through multiple related markets. Trade of electricity mainly takes place in the bilateral market. This means that the producers of electricity directly trade electricity to large consumers, traders or retail companies. Small end consumers acquire their electricity via the retailers. They are not allowed on the bilateral market. "Bilateral contracts are confidential, as a result of which there are no good data available regarding their price and duration. According to traders, however, contracts that are longer than a year are rare." (Vries *et al.* 2004:5) The APX is the Dutch power exchange. Electricity trade on the APX spot market is done day-ahead. Every day, each plant owner can bid a price and an amount he wants to produce for the next day, specified per hour of that next day. Hourly prices result from those bids together with the bids of the consumer side of the market. Prices are higher when demand relative to supply is larger. Bids are anonymous, but the market prices are public. Because this is the only electricity market of which the prices are publicly available, these prices are a valuable reference price for the bilateral market, described above. Consequently, prices of these markets are related. Prices on the spot market can be highly volatile. TenneT owns the shares of the APX spot market (Energie in Nederland 2006). Finally, the balancing market facilitates additional electricity generation to balance actual supply and demand in the moment. The actual use of electricity is unpredictable. Supply and demand of electricity must be equal (see above). The extra electricity has to be obligatory sold on the balancing market to the parties that predicted and bought less than their actual electricity withdrawals.

### **Focus on electricity generation**

The focus in this thesis lies on both the economic and physical layers of the *generation* side of the electricity sector. The first argument for this focus is that CET affects the generation of electricity. In contrast, CET

does *not* influence the demand for electricity, because that demand is assumed inelastic to changes in the price. Both parts are separate in the liberalized setting, as described above. Electricity is generated in different types of power plant that all use an energy source (e.g. a primary resource or wind) of the environment to produce electricity. Wanted and unwanted by-products are sold or released in the environment. Figure 5 displays an example. In this example, one generating company owns a power plant using coal and another using natural gas. The primary resources coal and natural gas are taken from the environment. After selling it on the electricity market, electricity produced in the two power plants flows to the electricity grid.

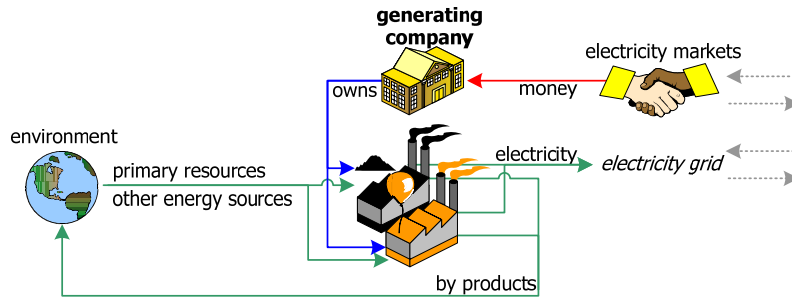


Figure 5. Example of a company that generates electricity.

### Technical aspects of electricity generation

This section gives an overview of the main technical aspects of electricity generation. Because CET affects the electricity generation portfolio, the main technical components are the power plants. These technical aspects are considered in the operational and investment decisions made by electricity companies, which are the topic of a later section.

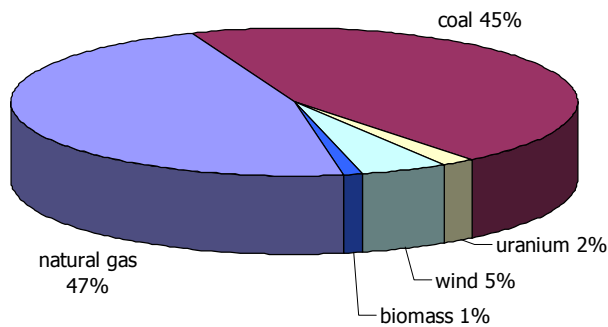


Figure 6. Energy sources for electricity generation in the Netherlands (based on data from CBS 2006).

Different types of power plant units are available to generate electricity. The overview of those types is for the purpose of this study structured by the energy source used, because the energy source is the main characteristic of a power plant. The electricity generation *portfolio* is the distribution of the types of plants in use. In the Netherlands, the main energy sources are natural gas, coal, biomass, uranium and wind, in the amounts displayed in Figure 6. In other countries, hydro plants are used in addition to these types. Hydro plants use the potential energy of water to produce electricity. In the Netherlands, mainly natural gas and coal are used for the production of electricity.

Table 2. Characteristics of energy sources.

energy source	availability	volume (per energy)	transport	CO <sub>2</sub> intensity	fuel costs per energy
natural gas	decreasing	large	pipeline	low	very high
coal	high	low	container ship, truck or train	high	low
uranium	high	very low	container ship, truck or train	none	very low
wind	uncertain	n/a	unnecessary	none	none
biomass	increasing	low	container ship, truck, train	none (for Kyoto)	medium

The different energy sources all have their own characteristics. Table 2 displays the main characteristics of the sources used for electricity generation in the Netherlands. A discussion per energy source follows on those characteristics and the main types of power plants using those sources.

Natural gas and coal are the main energy sources for Dutch electricity production. *Natural gas*, found in large amounts in The Netherlands, is the primary resource that produces the smallest amounts of CO<sub>2</sub> per unit of electricity created. Conventional natural gas resources are limited. With current levels of usage, the Dutch reserves will account for another 22 years and the world reserves 65 years (BP 2006). Gas is transported mainly through a pipeline structure. New developments towards the use of liquefied gasses increase possibilities of the use of other transport methods, such as train, boat or truck. Natural gas with prices equivalent for about 5 €/GJ (BP 2006) is an expensive fuel. Gas is burned in a combined cycle gas turbine. The hot, burned gasses drive a turbine that produces electricity.

*Coal* transport over long distances is affordable, as it is a solid fuel. World scale availability is large (155 years with current production levels according to BP (2006)). It contains more impurities and produces much more CO<sub>2</sub> per unit of electricity than natural gas, but equivalent costs are lower, 1.7 €/GJ (BP 2006). Coal is burned in a coal-fired steam power plant to produce steam, driving a turbine that produces electricity. New technologies for decreasing CO<sub>2</sub> emissions include a *clean coal* power plant. This is an upcoming technology, using a coal gasification process to create electricity and a pure CO<sub>2</sub> stream. This stream is stored in an empty gas field to prevent emissions of CO<sub>2</sub>.

*Uranium* is the energy source for nuclear power plants. The energy gained from nuclear reactions is large compared to combustion reactions. Consequently, uranium therefore is a relatively cheap energy source, around 65 €/kg (Stichting PeakOil-Nederland 2006). A nuclear power plant has thus low fuel costs and CO<sub>2</sub> emissions are absent. However, small amounts of nuclear waste are produced that have to be safely stored for long periods. The acceptability of nuclear power plants depends on the ongoing political debate. The Netherlands has currently one running nuclear power plant.

*Wind* is the energy source for electricity production in wind farms. Availability is hard to predict; it depends on the location and atmospheric conditions. Windmills produce no CO<sub>2</sub> emissions and have no fuel costs. Their output however depends on the distance between the mills. Their main environmental impacts are horizon pollution and damage to birds.

*Biomass* is a broad range of solid fuels with a natural origin, including animal waste, wood and plants. The fuels are burned in biomass power plants to produce electricity. Physical characteristics of biomass tend to be comparable to coal. Therefore, biomass power plants have comparable setups as coal based power plants. Only the prices of biomass are different to those of coal. Prices of biomass fuels are in the range of 30-100 €/ton (Department for Transport 2006), or 1-3.4 €/GJ.

Besides for electricity production, natural gas is in The Netherlands also used for house heating. The Dutch portfolio contains many combined heat and power plants (CHP): units with the joint production of heat and electricity. The heat or the electricity is then sold as by-product. In the absence of heat demand, some of those CHP plants can switch to produce electricity with a higher efficiency. Virtual power plants are an upcoming technology in which small power generating units are placed in households and being controlled by the energy supplier (Gasunie Trade Supply 2004). Complexity rises when one looks at facilities that combine the production of electricity with the production of heat and/or chemical products. Trigeneration combines the production of electricity with heat and chemical products (Dijkema 2001).

### **Economic aspects of electricity generation**

This section gives an overview of the main economic aspects of electricity generation. Rentability is the main criterion for operational and investment decisions of electricity producers. Consequently, the considerations in this section are relevant in the operational and investment decisions made by electricity companies, which are the topic of a later section.

Several types of costs play a role in operating an electricity-generating unit. Figure 7 displays a simplified overview of these costs. The distribution of the different costs depends on the type of power plant (see

the last paragraph and the modelling phase). First, there are investment costs to cover the development and construction of a particular installation. These costs occur once, at the start of the lifetime of the plant, but are generally very high. After the construction of the plant is finished, other costs play a role, namely fuel costs, costs for the needed CO<sub>2</sub> emission right (CO<sub>2</sub> costs) and several types of other operational costs. Those costs are displayed constant during the lifetime of the power plant, but are subject to many influences, such as change in fuel prices. Fuel costs only play a role in fuel consuming power plants (e.g. natural gas power plant). Electricity generating companies therefore depend heavily on fuel prices. CET introduces costs for CO<sub>2</sub> emission rights. Those can be significant for CO<sub>2</sub> intensive power plants. Other operational costs include maintenance. In reality, investment costs are paid before and during the complete construction period and costs for maintenance grow in the later stages of the lifetime of a power plant. The relative heights of investment costs and operational costs depend largely on the type of power plant. A discussion on actual values can be found in Appendix B.

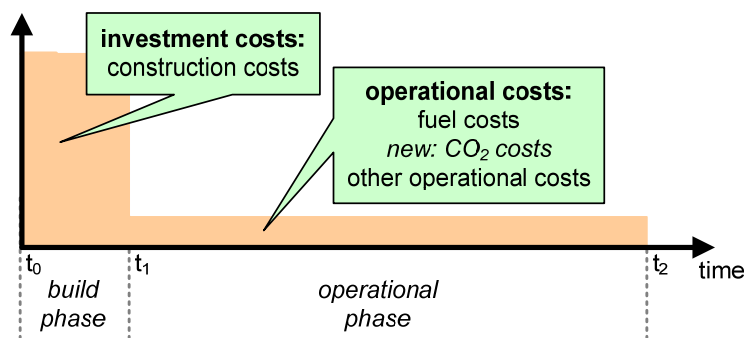


Figure 7. Investment and operational costs of a power plants.

### Operational and investment decisions in electricity generation

In this section, the decisions in electricity generation are discussed. The main two types of decisions are operational and investment decisions. First, operational decisions are discussed. Second, (dis)investments in power plants are discussed. It is important to look at the different considerations made in operational and investment decisions. Figure 8 summarizes the discussion of this section.

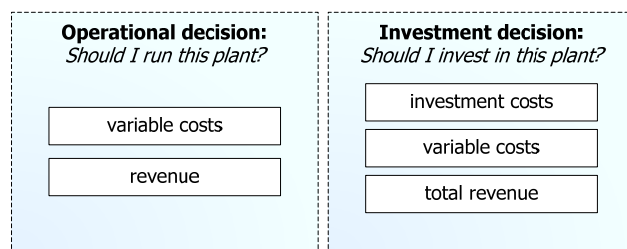


Figure 8. Operational versus investment decisions in electricity generation.

#### *Operational decisions in electricity generation*

Operational decisions in electricity generation deal with considerations of how to run a power plant. In those decisions, existing power plants are considered, thus it is relevant for an operational power plant *after* the investment decision and its construction. Investment costs have therefore been made in the past (between  $t_1$  and  $t_2$  of Figure 7). Under the assumption that electricity producers do not sell power plants themselves, investment costs are sunk and therefore irrelevant for operational decisions. The decision to run a plant is only based on variable costs: the bid on the market is based on costs that have to be made for running this plant. If the electricity producer expects to cover those costs with the revenue from selling the electricity, he makes the operational decision to run the plant. Any revenue over the variable costs contributes to covering the investment costs made earlier. That means, as long as the technical lifetime of the plant has not been reached (the plant is still functional,  $t_2$  of Figure 7 is not reached), some

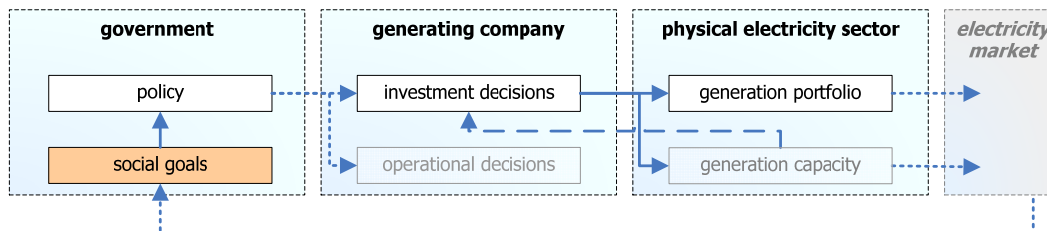
of the sunk investment costs might be covered by running the plant. As implied by this discussion, investment decisions that were made in the past determine the current operational decisions.

For combined heat and power plants (CHP), a form of joint production, electricity producers consider operational decisions differently. Depending on the function of the equipment, CHP can be heat- or power-driven. The argument above holds for power-driven CHP units. However, if it is heat-driven, the demand for heat is dominant over the demand for electricity. Such CHP units are run only in case of heat demand. Electricity is used or sold as a by-product. Some CHP facilities are not heat- or electricity-driven, but are able to switch to produce electricity only to be able to earn money with the facility at the absence of heat demand.

#### *Investments in electricity generation*

Before the electricity sector was liberalized, investments were planned by the SEP, representing all Dutch electricity producers. Because of this planning, at all times enough (reserve) capacity was available to cover the demand and prevent blackouts. In a liberalized market, these investments are not centrally planned. Individual and autonomous players on the market now make the investment decisions. Government still has influence on these decisions. As shown in Figure 9, government develops additional policy to be able to secure social goals. An example of those social goals could be affordability of electricity. Because generating companies operate autonomously, policies function as indirect instruments. CET and subsidies are examples of indirect instruments that governments use to change investment decisions of electricity companies. Policies can also influence operational decisions (e.g. fuel taxes that increase fuel costs). The actual impact of policy is often unknown, because the companies are autonomous. They have their own strategic agendas.

When a party considers an investment decision, at time  $t_0$  of Figure 7, they evaluate the life cycle costs: investment costs and operational, variable costs, based on expected output of electricity. In addition, the expected revenue from selling the produced electricity is calculated. Because the lifetime of power plants is long, much uncertainty resides in investment decisions. Several methods used to underpin investment decisions reflect that uncertainty. For instance, producers use scenarios to extrapolate the range of possible futures that are relevant for the decisions. The range is an indicator for the uncertainty. The discounted cash flow method uses interests and inflation rates to determine the value of the costs and the revenue during the lifetime of the power plant. Real options theory values an investment in new power plants as an opportunity (Neufville 2001). However, the decisions are in reality not only based on economics. Other influences are market power, financial strength and the management style of electricity producers. The management styles of electricity producers for instance include their environment mindedness and nuclear fear. It is observed that in reality different market players exploit different types of power plants. Therefore, the differences caused by the other factors than economics must be significant. This might also imply that environmental policy set up by government has different effects on different players.



**Figure 9. Realizing social goals in a liberalised electricity sector.**

Whether a power plant is in base load, peak load or reserve depends on the relative cost levels. Base load, peak load and reserve are distinguished based on the differences in cost characteristics. If the variable costs of a plant are relatively low, it is part of base load: the market outcome is that the power plant will always run, even if demand is low. If variable costs are higher, the plant will only run when demand is high, under peak load. Some power plants have such high marginal costs, that on an average day they do not run at all. They are part of reserve. Usually new power plants are more efficient and become part of

base load. That means that new plants push older ones out to peak load and reserve. Consequently, during its lifetime, the role of power plants in general shifts from base load, through peak load towards reserve. The revenue generated from selling electricity depends – next to the electricity prices – on the actual output of electricity. If a power plant is part of reserve capacity, actual output will be relatively small. The role of a power plant during its complete lifetime therefore needs consideration to indicate the life-cycle profitability of that plant.

Investment decisions shape the generation capacity portfolio. Not only the types of power plants but also the *amount* of capacity is relevant. Although the focus of this thesis is *not* on adequacy of generation capacity – and thus *not* on the amount of capacity – one important phenomenon is mentioned here. Because of a combination of risk-aversion and too short time horizons of market players, a delay in investments can occur, also known as investment cycles (Vries *et al.* 2004). Scarcity in the market will lead to higher prices, but result only later in new capacity, due to the long construction times of new capacity. This scarcity is attractive for generating companies on the short term, because that means more profit of the electricity sold. It is therefore more attractive to invest too late, than to invest too soon. More parties will invest in that period of scarcity and new capacity will only be ready when capacity scarcity is further increased. This results in overinvestment, and overcapacity. Prices drop, because of the lack of scarcity. Investments will stay away for a long period, until it is again too late. This is a phenomenon observed in many capital-intensive industries.

## 2.6 Impacts of CET on operational and investment decisions in electricity generation

CET is supposed to reduce CO<sub>2</sub> emissions for the sectors involved. These sectors include a number of industrial activities, such as electricity generation. CET has influence on the operational decisions and on the investment decisions made by electricity producers. First, the impacts on operational decisions are discussed. After that follows a discussion on the impacts on investment decisions.

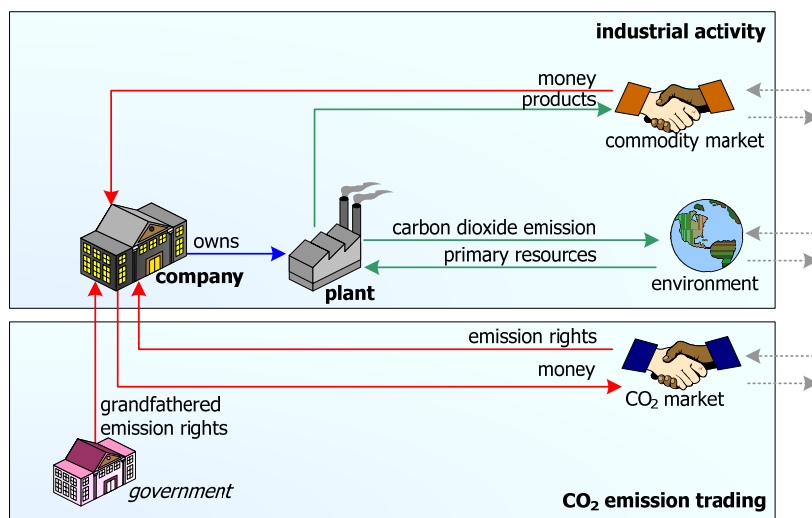


Figure 10. Operational impacts of CET on industrial activities.

### Impacts of CET on operational decisions in electricity generation

Figure 10 displays the short-term operational impacts of CET on electricity generation. An industrial activity in general takes place in a plant, a physical facility in which processes take place. An industrial company owns that facility. Depending on the processes inside this power plant, primary resources are converted to products and emissions. The products are exchanged for money with other companies, which here are represented in a commodity market. The primary resources are retrieved from the environment. Emissions are released back in.

Because of the installation of CET, the government imposes the need for companies to acquire emission rights. This means that extra costs are imposed on activities that emit CO<sub>2</sub>.



Two factors determine the *operational impacts* of CET. The first factor is the price for emission rights. Lower prices have less impact, because costs for rights are lower relative to other production costs. The second factor is the CO<sub>2</sub> intensity, defined as the CO<sub>2</sub> emission per product produced. If there are alternatives that differ in CO<sub>2</sub> intensity, CET affects the attractiveness of those options. In electricity generation, most facilities are inflexible in changing the production process to decrease CO<sub>2</sub> intensity. Most power plants need a certain fuel as input and the CO<sub>2</sub> emission follows from that choice. Bi-fueled plants are getting more attractive for this reason.

However, to show the impact that CET can have (on industrial activities in general) the following example is used. Table 3 shows a simple example to illustrate this impact. Two alternative options to produce a certain product have different CO<sub>2</sub> intensities. The following formula is used to calculate the costs for the alternative options.

$$\text{total costs [€/ton]} = \text{production costs [€/ton]} + \text{CO}_2 \text{ intensity [ton CO}_2\text{/ton]} \times \text{CO}_2 \text{ price [€/ton CO}_2\text{]} \quad (2)$$

In Table 3, the outcomes for three CO<sub>2</sub> prices are calculated. Without CET, alternative 2 is economically most attractive. When CO<sub>2</sub> emissions are priced, absolute prices change, but because of the differences in CO<sub>2</sub> intensity, also the relative costs change. At a price of 10 €/ton CO<sub>2</sub>, alternative 2 is still the best, but they are much closer. At higher prices, such as 50 €/ton CO<sub>2</sub>, alternative 1 is more attractive: CO<sub>2</sub> costs than mainly determine the attractiveness of the options. The CO<sub>2</sub> price at which both alternatives have equal costs can be calculated with the formula, stated above:

$$\begin{aligned} \text{production cost}_{a1} + \text{CO}_2 \text{ intensity}_{a1} \times \text{CO}_2 \text{ price} &= \text{production cost}_{a2} + \text{CO}_2 \text{ intensity}_{a2} \times \text{CO}_2 \text{ price} \\ 90 + 1 \times \text{CO}_2 \text{ price} &= 60 + 2 \times \text{CO}_2 \text{ price} \\ \text{CO}_2 \text{ price} &= 30 \text{ [€/ton]} \end{aligned} \quad (3)$$

The break-even CO<sub>2</sub> price is 30 €/ton. For CO<sub>2</sub> prices above 30 €/ton, alternative 1 is more attractive. In contrast, for lower prices, alternative 2 is more attractive.

This example shows that higher prices can have a larger impact on operational decisions, because the impact on some activities is larger than on others, based on the relative CO<sub>2</sub> intensity of alternatives. On short term, that creates a competitive disadvantage or can have an increasing effect on prices of sold goods for relatively CO<sub>2</sub> intensive industrial activities. Because electricity generation is inflexible to this respect, operational impacts are only the introduction of more costs. Change of production can only be achieved by investments.

**Table 3. Example of CET impact on alternative activities with different CO<sub>2</sub> intensities**

	<i>alternative 1 (per ton product)</i>	<i>alternative 2 (per ton product)</i>
CO <sub>2</sub> intensity	1 ton CO <sub>2</sub>	2 ton CO <sub>2</sub>
production costs <i>excluding</i> CO <sub>2</sub>	€ 90	€ 60
<i>no CET: p = € 0 per ton CO<sub>2</sub></i>		
CO <sub>2</sub> costs	€ 0	€ 0
production costs	€ 90	<b>€ 60</b>
most attractive option: 2		
<i>CET: p = € 10 per ton CO<sub>2</sub></i>		
CO <sub>2</sub> costs	€ 10	€ 20
production costs	€ 100	<b>€ 80</b>
most attractive option: 2		
<i>CET: € 50 per ton CO<sub>2</sub></i>		
CO <sub>2</sub> costs	€ 50	€ 100
production costs	<b>€ 140</b>	€ 160
most attractive option: 1		



### Impacts of CET on investment decisions in electricity generation

Considering a longer term, companies may take decisions that structurally change their electricity generation portfolio: they can make investment and disinvestment decisions. CET mainly affects those decisions. A diagram of that impact is drawn in Figure 11. The grey arrows are significant exogenous influences. The bold arrows indicate the main connections between the electricity sector and emission trading.

Electricity producers take forecasts of costs and revenue into account in investment decisions (recall Figure 8). Traditionally, they were investment costs, fuel costs and other operational costs. The expected revenue originates from selling the electricity. CET introduces a new type of costs, namely the costs for CO<sub>2</sub> rights. Investment decisions and disinvestment decisions by individual electricity producers change the generation portfolio. In other words, the mix of power plant types can change as a consequence of changes in the relative attractiveness of available power plant types. Because the different power plant types have different CO<sub>2</sub> intensities (see Table 2), electricity producers can change the CO<sub>2</sub> intensity of power generation as a whole through investments in different power plants. The mix of power plant types together with the amount of electricity production of individual installations determines the CO<sub>2</sub> emission. Consequently, the actual CO<sub>2</sub> emission can change because of a shift in generation portfolio.

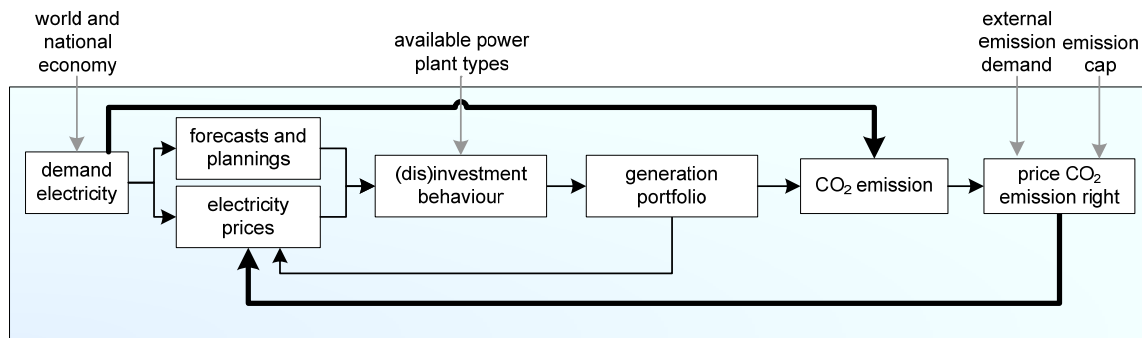


Figure 11. System diagram of CET and electricity generation.

The speed of the portfolio shift can increase by disinvestment in operational power plants. Because of the impacts shown above, the profitability of specific installations can decrease. Consequently, companies can decide to dismantle installations if they expect that none of the sunk costs can be recovered.

Moreover, CET also has an influence on the price for marginal costs for production of electricity (shown in the lower bold arrow of Figure 11). Assuming that the demand for electricity is inelastic to price (Vries 2004:33), costs for CO<sub>2</sub> emission rights caused by electricity production are directly added to electricity prices and the variable costs of electricity production with CO<sub>2</sub> emitting power plants increase. The price for these rights is based on actual emission, the emission cap, the emission demand from electricity generation and the emission demand from other sectors. The price for CO<sub>2</sub> rights determines the strength of the signal that causes the portfolio shift.

### 2.7 Criteria for assessing the impacts of CET on electricity generation portfolio development

As already indicated, the goal of CET is to reduce CO<sub>2</sub> emissions to Kyoto agreed levels. This should be achieved by a portfolio shift towards a less CO<sub>2</sub> intensive mix of power plant types. In this paragraph, this goal is operationalized for electricity generation. The criteria derived are to be tested by the model that is presented in part II of this thesis. Figure 12 gives an overview of the used criteria.

- The first criterion is that a reduction of emissions by electricity generation should be achieved relative to a situation without CET.
- The second criterion is that the cap on the emissions for the electricity sector, as set by the government, should be maintained.

- The third criterion is that the reduction should be efficient. This means that the achieved reduction is against the lowest costs possible and no costs are made unnecessary to the reduction.

Values on the last criterion cannot be calculated. Therefore, indications are used for that criterion. Indications for unnecessary costs are for instance influence on investment cycles or on the adequacy of electricity generation capacity. These criteria are used in chapter seven to assess whether CET leads effectively to a reduction of CO<sub>2</sub> emissions.

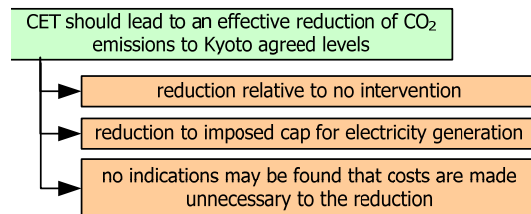


Figure 12. Operational goals of emission trade system.

## 2.8 Conclusions

CET is implemented in the EU as an instrument to reduce emissions. For electricity producing companies this means that emission rights are needed to generate electricity. The company can acquire them in two ways. First, a limited amount of rights are supplied by the government for free. Second, if additional rights are needed, these rights can be purchased on a dedicated market. The total amount of rights is fixed, but possibilities exist to acquire rights beyond the national cap.

On the short term, costs imposed by the CET system decrease the profitability of CO<sub>2</sub> emitting power plants. Impact on operational decisions is small because electricity production installations are bound to the use of specific fuels and the according emission of CO<sub>2</sub>. On the longer term, a change can occur in the investments made in new installations and may lead to early disinvestment in installed capacity. In the liberalised electricity sector, generation type and capacity is no longer subject to central planning and coordination. Investment decisions are now made by autonomous market players. Electricity producers can invest in a set of different power plant types, decided on the basis of forecasts of life-cycle costs for power plants. During operation of an existing plant, however, the investments costs are sunk.

Criteria are derived to test the effectiveness of CET in reducing emissions caused by electricity generation. Reductions should remain within the set cap for electricity generation and CET must cause reductions relative to no intervention. No indications may be found that costs are made unnecessary to the reduction. These criteria are used in part III to assess the impacts of CET with model that is built in part II.

## 3 Methodology

### 3.1 Introduction

This chapter gives an overview of the methodology adopted in this thesis. The problem was introduced and defined in the first chapter and chapter two addressed the assessment criteria that are to be tested with the model. This chapter discusses the research process, methods and modelling paradigm. The second paragraph presents the research process. The third paragraph elucidates on the methods used in this process. Because modelling is very important in that process, a comparison of four main modelling paradigms follows. Justification of the choice for agent-based modelling precedes a thorough discussion of agent-based modelling, together with an example to illustrate the terminology. The chapter ends with conclusions.

### 3.2 Research process

The research process of this thesis is based on (Nikolic *et al.* 2004; Nikolic *et al.* 2006; Nikolic *et al.* 2007). It contains all the steps that were used to obtain the results of this thesis. Figure 13 displays an overview of the steps of the research process.

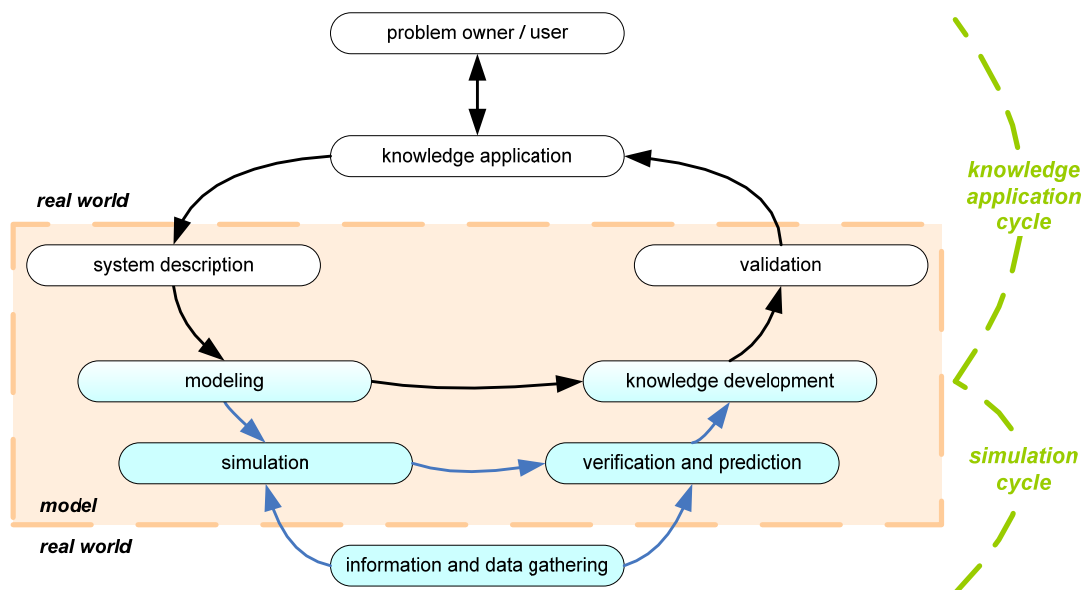


Figure 13. Research process (Nikolic *et al.* 2007).

The general idea of this process is that two cycles iterate continuously: the knowledge cycle and the simulation cycle. In the ‘knowledge cycle’ (the white blocks) knowledge is used to develop a conceptual model that leads to conclusions that enriches the existing body of knowledge. In the ‘simulation cycle’ (the blue blocks), simulation runs are performed to get quantitative outcomes that also lead to increased knowledge. The cycles partly overlap.

### Knowledge cycle

The starting point for this research is the (scientific) knowledge that currently exists. This also includes the researchers' perception of reality. This knowledge is the basis for a systems description that identifies the structure of the components in the system relevant to a specific problem. For this thesis that means drawing a systems diagram of the impacts of CET on electricity generation portfolio development. That system description can contain a conceptual model. Qualitative conclusions can result from that model on a specific problem. Addressing these issues and analysis and validation of the results builds new knowledge. That completes an iteration of the knowledge cycle. The use of the simulation cycle can give support to and quantify these results in order to develop more knowledge.

### Simulation cycle

The conceptual model can instead of directly finishing the knowledge application cycle, be the starting point for a simulation model. Building those models is an iterative process in which a model is further developed. The simulation cycle contains modelling steps such as modelling the needed concepts, by using information of the real world and of the knowledge application, verifying, validating and running the models and interpreting the results. The model development process of this thesis contains these steps. Simulation runs generate results that give insight in possible future system behaviour. Knowledge develops based on these results.

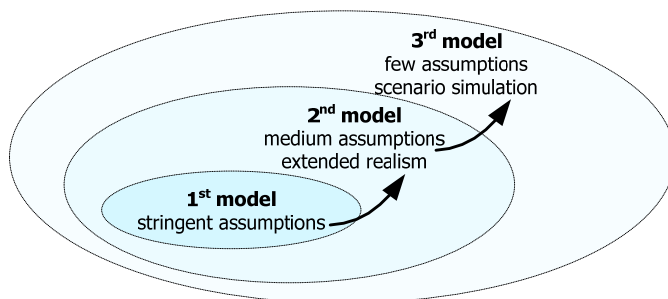
## 3.3 Methods in the research process

A number of methods structure the *process* and *content* of this research (see Table 4). The used methods are the three-layer model, the onion model, creativity techniques and scenario development. The use of the methods is in the modelling phase of the research process. They address and structure different aspects of the structure and the content of that phase.

**Table 4. Methods used and their place in the research process.**

<i>process</i>	<i>content</i>
onion model	three-layer model
creativity techniques	scenario development

The onion model structures the process in which the model itself was developed; it structures the model development process, on a meta-level. Creativity techniques enhance the creativity of the output. The three-layer model structures the interaction of physical and social components in the model. Scenario development structures the environment surrounding the model; scenarios grasp all the needed data and factors that are relevant for the model but not determined by it: all exogenous factors. A separate discussion of those four methods follows.



**Figure 14. Onion model.**

### Onion model

The '*onion model*' structures the model development *process*. Figure 14 illustrates that several iterations of model development cycles have increasing complexity by losing stringent assumptions. This is a visualisation of the cyclic character of the model development process, in which ideas and results of a

model are part of the input for developing the next model. This is preferred because building a complete model in one time is practically impossible. It also speeds up the overall modelling process, because earlier insights from the model come from preliminary models produced in the modelling process. In the reflection on the model development process of chapter nine, specific attention goes to the use of incremental and iterative design and the trade-off between the use of those two methods for design. That trade-off can be seen as an extension of this onion model.

### Three-layer model

The relations and communication in systems with technical and social components can be structured in three distinct layers with the three-layer model (Dijkema 2006). Technical components are for instance power plants. Social components are the actors. By structuring those layers, the different types of relations and interaction can be addressed separately and visualisation of those relations is easier to understand. Figure 15 displays the three layers used in this thesis. This diagram is based on personal communications (Dijkema 2006).

The lowest layer contains the *physical assets*. Technological installations interact on a level of physical flows of goods and materials, such as fuels and electricity. Physical flows of goods occur because actors agree upon their delivery in contracts. Therefore, the activities in the physical layer are the consequence of operational decisions by actors. The middle layer contains *operational management*. On this level, actors interact: they negotiate, enter into contracts and transfer money for delivered goods or services. Actors make operational decisions based on their arrangements that have consequences for the physical layer: operational decisions make the agreed physical transactions happen. Interaction in the layer of *strategic management* contains ownership relations of actors. Investment and disinvestment decisions have consequences for the products that a firm can make and therefore for the possible contracts that a firm can enter in (which is, as mentioned above, part of the middle layer). Since investment and disinvestment decisions shape the set of physical installations (such as the electricity production portfolio), the top layer also controls the physical layer.

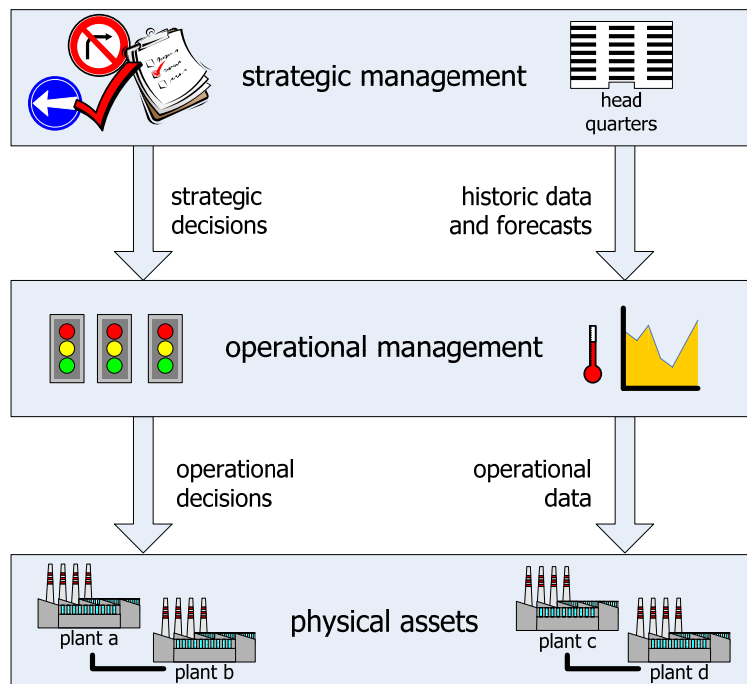


Figure 15. Three-layer model (Dijkema 2006).

The physical lifetime of an average power plant is in the order of 20-40 years. Disinvestment and investment decisions, also called strategic decisions, cause change in the strategic layer. Consequently, changes in the top layer occur on a long-time scale. In the operational layer, changes occur on medium time-scale. Actions are based on contracts that are agreed upon more often, on a monthly to yearly time-

scale. The physical layer has even shorter relevant time-scales, since delivery of goods can change as often as agreed upon in contracts.

This three-layer model is used in this thesis to structure the relations and interaction in and between the social and physical components. The arrows in the picture on the cover of this report are based on this concept. The arrows of the strategic layer define ownership of technological installations and have a blue colour. The relations in the operational layer are contracts, they have a red colour. Finally, interaction of the physical layer, the physical delivery of goods is drawn as arrows with a green colour. The interaction of the social and technical components is thus structured with this model.

### **Creativity methods**

Several creativity methods are used in the model development process. Many discussions with a creative character were held with several experts within the Energy and Industry Group in order to structure the development process of the environment in which the model is developed, presented in part II of this thesis.

The used creativity methods also include numerous soft techniques as parallel working on multiple subjects and brainstorming. Those techniques are used to enrich the model development process and optimize the quality of the outputs within the scope of the thesis project. More on that can be found in the reflection on the model development process in chapter nine.

### **Scenario development**

Scenarios describe the playing field the agents are in: an abstraction of a possible future. Environment scenarios are applicable for this goal (Enserink *et al.* 2002). Factors of relevance are factors that are uncertain in the future and that have a potential influence on the problem. Factors need to have an influence on the problem to be significant. They need to be uncertain to be useful for scenario analysis. Factors with low uncertainty should be a model parameter, not a scenario factor. Variation in trends and values of those factors determine the range of possible futures.

The identification of driving forces limits the number of scenarios to a workable amount. Driving forces are very generic, abstract developments, such as the world economic growth, that are the cause for these factors. A limited number of driving forces is used to build the scenario space. All driving forces are an axis of the scenario space. By assuming that the list of relevant and uncertain factors is complete, the scenario space contains all possible futures for the system. The selected scenarios are specific, static locations in this scenario space. Specific scenarios (locations in the scenario space) are sets of values and trends for the factors that constitute the driving forces. Note that for the model in this thesis, this means that scenarios define the trends of the external world in which agents do their business. For more information on the use of this method, see chapter four.

## **3.4 Comparison of modelling paradigms**

Different paradigms exist for modelling dynamic systems such as the system of this thesis. The four main paradigms are system dynamics, dynamic systems, discrete-event modelling and agent-based modelling. The paradigms all have different *perceptions* and use different methods to represent a system. This paragraph gives introductions to the paradigms. After that, a comparison is made by a discussion of the types of systems that can be modelled and the types of questions that can be answered by using those paradigms. In the next paragraph, the choice for agent-based modelling is justified.

### **Introduction to the paradigms**

All four paradigms are introduced shortly. Borshchev and Filippov (2006) illustrated an overview of the different paradigms that was reproduced in Figure 16. The paradigms use different approaches towards problems and systems. First, an introduction is given to all of the paradigms, their origin, the perception on the world and their applications. After that, they are compared. An overview of the differences, such as the distinction of the levels of abstraction (that Figure 16 shows) will follow after these introductions.

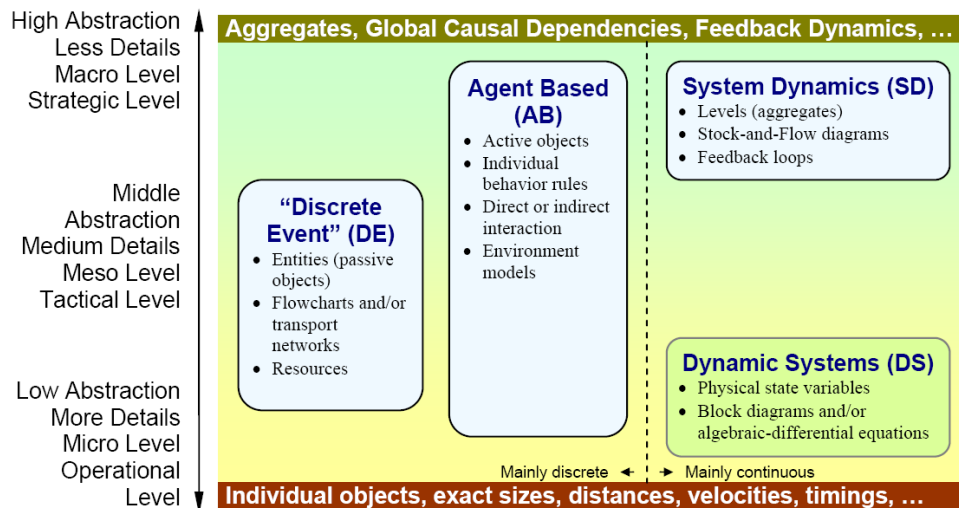


Figure 16. Modelling paradigms (Borshchev *et al.* 2006).

*System Dynamics* was developed by an electrical engineer Jay W. Forrester in the 1950s. System Dynamics is "the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise" (Forrester 1958). The perception of system dynamics is that processes in the world are represented in terms of stocks (e.g. of material, energy, knowledge, people, money), flows between those stocks, and information that determines the values of the flows (Forrester 1969). Single events do not exist; events are abstracted to an aggregated view on feedback loops and delay structures. In practice, this means that models contain global structural dependencies. Mathematically, an SD model is a system of differential equations. Individual unique characteristics and behaviour of entities cannot be modelled as such. For a commodity such as electricity this is preferred, since electrons are all the same and representation as a flow is appealing; we even see it as a flow instead of discrete electrons. For other entities this is different: if a number of players on a market all are assumed to behave alike, the market can be aggregated to follow a behavioural pattern that can be translated to a differential equation of a system dynamics model. But if the players all have unique behaviour that is significant, they cannot be modelled as such. System dynamics is used to find long term dynamics in liberalised electricity markets by Orsina *et al.* (2006). This extensive study compared the relative attractiveness of gas and coal based power plants. The time scale is still within twenty years. That study assumes criteria other than economic are irrelevant. System dynamics cannot address individual behaviour.

*Dynamic Systems*, an ancestor of system dynamics, perceives that the physical world can be modelled by a number of state variables and differential equations over these variables. Variables have direct physical meaning, such as location, velocity, acceleration, pressure, concentration. They are inherently continuous, not aggregates of multiple entities. The mathematical diversity and complexity in dynamic systems can be much higher than in system dynamics. Dynamic systems are mainly used to model the control of physical systems, such as (parts of) chemical plants. Dynamic systems is only applicable on physical systems. It is not used for systems that also have social components (such as actors that behave) as the subject of this thesis.

*Discrete-event modelling* is a modelling approach that perceives that the world consists of passive entities that are to be routed and processed through systems. This approach roots in the 1960s when Geoffrey Gordon conceived and evolved the idea that entities are passive objects that represent people, parts, documents, tasks, messages, etc. They travel through the blocks of the flowchart where they stay in queues, are delayed, processed, seize and release resources, split, combined, etc. Discrete-event modelling may be considered to be a global entity processing algorithm, typically with stochastic elements. The idea is that entities flow as the model prescribes: the entities themselves are not making the decisions. It is mainly used for simulation of logistic processes to give insight in entity flows and resource sharing. Discrete event modelling has been used to model the generation side of the electricity sector by Gutierrez-

Alcaraz and Sheble (2006), but their research was only limited to two electricity producers. Other research with respect to electricity focused on short time scale impacts of flows in physical systems.

*Agent-based models* originate from many research areas: artificial intelligence, complexity science, game theory, object-oriented programming and human-computer interface design. No generic definitions of models and agents exist in the current literature (Schieritz *et al.* 2003). The definitions used in this thesis will be given and discussed in paragraph 3.6, but in general can be said that agent-based models consist of agents that interact. Agent-based models are essentially decentralized; there is no such place where the global system behaviour (dynamics) is defined. Instead, the modeller defines behaviour at individual level, in agents. The global behaviour emerges as a result of the individual agents' behaviour, each following their own rules for behaviour, living together in some environment and communicating with each other and with the environment. That is why ABM is also called bottom-up modelling. Agent-based models are mainly used in social sciences for behavioural structure of groups of people by the definition of individual behaviour. SAM Corporate Sustainability Assessment (2006): "Agent-based models are used to address dynamic systems. These models emphasise modelling behaviour at the lowest practical level, with an interest in studying the emergence of spatial arrangements and agent interactions, as well as the evolution of strategies for agent interaction with the environment and other agents. [...] Agent-based models are well suited to model strategies of different stakeholders, their interactions and the outcome of such interactions." Agent-based models exist for electricity markets, and many proposals were published recently (e.g. Biernatzki *et al.* 2004; Borrie *et al.* 2004; Liu *et al.* 2005) to use agent-based simulation to model impacts of emission trade on electricity markets.

### Comparison of the paradigms

An overview of the main characteristics of the four paradigms is stated in Table 5. Detailed discussions of system dynamics and agent-based modelling can be found in (Schieritz *et al.* 2003) and on all four paradigms in (Borshchev *et al.* 2006). The different paradigms are compared by a discussion of the main characteristics.

**Table 5. Differences between system dynamics and agent based modelling.**

	<i>system dynamics</i>	<i>dynamic systems</i>	<i>discrete-event</i>	<i>agent-based</i>
perspective	top-down	top-down	top-down	bottom-up
level of abstraction	(aggregate) relations	relations	flow structure	individual rules
main building block	feedback loop	mathematical operation	flow blocks	agent
mathematics	differential equations	differential equations	stochastics	logic, stochastics
unit of analysis	structure of system	structure of system	processing entities	agents' rules
structure of system	emerging <i>dominant</i> structure	emerging <i>dominant</i> structure	static structure, with emerging bottlenecks	emerging structure
handling of time	continuous	continuous	discrete	<i>mainly</i> discrete
results	levels and flows	physical interaction	flows of entities	emerging behaviour

The main differences between the four paradigms are caused by a different *perception* of the world, different sets of glasses through which the world is viewed. In system dynamics, the world is built of stocks of materials or knowledge and flows between those stocks. In dynamic systems, the world is a set of physical variables and because they are related, the values change. The discrete-event paradigm sees structure in flows of discrete materials or documents. Agent-based modelling sees a collection of individual agents making autonomous decisions to reach their own goals, based on interaction with other agents and information they have or acquire.

These perceptions are relevant for the build-up of models. In most paradigms, a top-down perspective is used. The overall structure: the main components *and* their relations are explicitly modelled, because they are assumed to be known quantitatively. All relations can be quantified and the interaction of the parts of this structure is studied during simulations. For system dynamics and dynamic systems, the focus is on feedback loops that determine the output of the total system. For discrete-event models, the focus is on bottlenecks: for instance queues of people before a desk. In contrast, this perspective is fundamentally



different for agent-based modelling, in which the *relations* are not explicitly modelled, but emerge from the decisions that individual agents make, it is a result from their interaction.

The level of abstraction, displayed as main distinction in Figure 16, follows directly from the perception and coincides with the main building blocks as well as the mathematics used. System dynamics describes aggregate relations with feedback loops, mathematically modelled as differential equations. That means that abstract, global relations are used to describe actual events. Dynamic systems does not use those aggregate relations, but only physically meaningful variables, translated to mathematical operations, also described with differential equations. They have very concrete physical meaning. Flows of passive entities in discrete-event models are modelled by flow blocks that use stochastic variables. Individual entities are thus explicitly modelled as well as events that occur. However, the entities are not central, the *flow* of entities is. With agent-based modelling, the actions are autonomously undertaken by those entities, they themselves decide what to do and where to go: the entities are central. Only *potential actions* of agents are modelled on the system level. The agents themselves decide on using those possibilities.

Discrete handling of time means that events are explicitly modelled to happen at a certain moment in time. In contrast, continuous handling of time does not model individual events but change in variables resulting from those events. For instance, consider the modelling of birth and death for a population. In the continuous time, birth and death are described as rates that depend on the population size and other factors (such as distribution of age and welfare). However, in discrete time, two persons can be said to have a certain chance that they give birth at a certain moment in time. The same persons have a certain chance of dying. Both *events* occur at discrete moments in time with a change in the size of the population as consequence. System dynamics and dynamic systems prescribe the use of continuous handling of time. Discrete-event prescribes discrete handling of time as the name of the paradigm implies. The agent-based modelling literature is ambiguous on this point, but mostly, discrete handling of time is used.

The data needed in the different modelling techniques are different. In system dynamics and dynamic systems, much reliable, quantitative data on relations and system level behaviour are needed to be able to come to the differential equations of the model. The relations in these types of models build multiple feedback loops that are studied upon. For discrete-event models, detailed quantitative data are needed on the flow structures that are modelled. With agent-based modelling, the data needed are on the goals, the state and the behaviour of entities: thus what purpose and characteristics the entity has and what the entity can do.

The main differences, summarized in Table 5, are thus caused by a different perception of the world. This means that the choice made in the next paragraph should fit with the type of insights that are needed to answer the main research question.

### 3.5 Reasons for choosing agent-based modelling

For this thesis, the choice of paradigm is agent-based modelling. In short, the basic argument is that an agent-based approach intuitively fits a system in which individual investment decisions by individual actors, seen as discrete *events*, are central. The arguments, advantages and disadvantages are summed up in this paragraph. They follow from the comparison and the systems description in the previous chapter.

The main argument for using agent-based modelling is that decision rules of autonomous agents are the central object of study. As was said earlier, the actual impact of CET on electricity generation portfolio development goes through the investment and disinvestment decisions that individual actors take. Two aspects of this view are important: first that *decisions* play a central role and second that *individual* actors take those decisions. This coincides with reality, because electricity companies have, in the current market setting, the autonomy to decide on their own investments. The advantage of looking at individual decisions increases, because in reality, different companies seem to apply different rules. Soft factors play a role and companies have management styles and market positions that result in differences in types of power plants per company. That characteristic can only be modelled explicitly with an agent-based approach.

Discrete-event modelling does not recognize *active* entities: documents or people do not make decisions in that paradigm; they go somewhere based on their properties, not based on their decisions. It would be hard and maybe even impossible to grasp investment and disinvestment decisions in passive objects only. In conclusion, agent-based modelling is more attractive than discrete-event modelling, because the distinction between passive and active objects can be made. System dynamics does not model decisions explicitly and no individual entities are distinguished. That means that aggregates should be modelled for the individual actors and power plants and their decisions. That would be inconvenient and counter intuitive. With dynamic systems, aspects, variables or components without a physical meaning cannot be modelled. Because both social and technical components are relevant, that paradigm is not applicable.

Besides the fact that the use of active and autonomous agents next to other passive entities is preferred above only passive entities or aggregates, other advantages exist. For instance, agent-based modelling is object-oriented: everything we see as an object is explicitly modelled as an object. Each object completely stands alone, can be replaced by other objects or even models. This opens possibilities to using existing models, exchange parts with other modellers and have a clear and structured model as well as the model development process. The combination of continuous and discrete time and entities in this problem is useful. Entities are discrete, as are events, but many entities, such as capital, electricity and gasses are continuous by nature (they flow) and it is attractive to address that nature as it is; that is only possible by using agent-based modelling as paradigm. Finally, an advantage is the ease in which irrational behaviour of actors can be modelled by the use of stochastic elements in the decision logic of agents.

These are all advantages, but partly their benefit will only show after this project is finished. In later stages, these can be exploited. Flexibility for use of the model also after this project was stated as important in the outline of the scope in paragraph 1.5 and these advantages thus coincide with that objective.

Agent-based modelling also has disadvantages. First, no complete packages of software tools are available for agent-based modelling. Even with the software tools that are available, many developments are needed to get a complete and functional package. Many resources go into that process that could otherwise be used on the content of the model. Besides that disadvantage, the outcome of the development process for the software tools has benefits on longer term, since after this project a basic environment is ready for use and expansion. Because the tools are shared, possibilities for exchange of model parts are increased by using this approach. Second, validation methods are not adequate. Because the field of agent-based modelling is ambiguous and new, validation has not been fully addressed. Validity is in this thesis defined as fit for purpose. Literature on validity usually focuses on verification that means looking for consistency only. Besides full verification, an attempt will be made to validate the model, with techniques that are found in literature (Daalen *et al.* 2001; Qudrat-Ullah 2005).

For these reasons, agent-based modelling is chosen to elucidate the impacts of CET on portfolio development in the electricity sector.

### 3.6 Description of agent-based modelling

Now agent-based modelling (ABM) is selected, the description of the previous paragraphs is elucidated with definitions of an ABM and an agent. 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 *et al.* 1996; Axelrod 1997). An ABM thus is a set of ‘agents’ with certain properties that are interacting.

The use of ABM is, as was stated above, well defined by SAM Corporate Sustainability Assessment (2006): “Agent-based models are used to address dynamic systems. These models emphasise modelling behaviour at the lowest practical level, with an interest in studying the emergence of spatial arrangements and agent interactions, as well as the evolution of strategies for agent interaction with the environment and other agents. [...] Agent-based models are well suited to model strategies of different stakeholders, their interactions and the outcome of such interactions.”

### Components of agent-based models

Because no standard structure of agent-based models is universally accepted, the setup of agent-based models is domain-specific. The discussion on the components of agent-based models is therefore also partly specific for this thesis. The structure of an agent-based model used in this thesis is displayed in Figure 17.

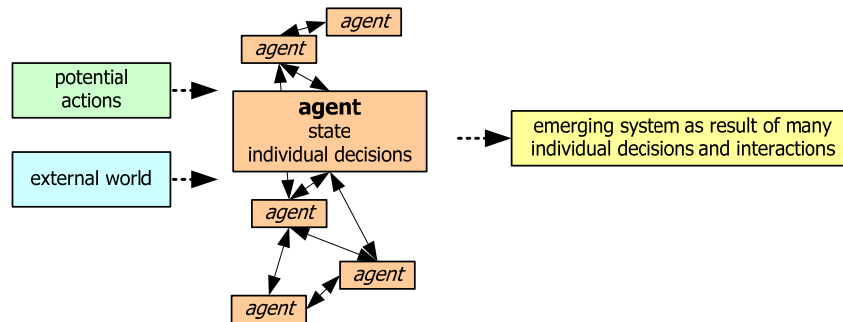


Figure 17. Agent-based model structure and components.

The sequence of *potential* actions defines in general the structure of an ABM. That sequence is a list of actions agents *can* undertake. Agents themselves decide whether and how they act; the list provides the overall structure of possible actions. The main components of an ABM are the agents. An elaborate discussion on their build-up will follow below. Next to the agents, there is an important role for *passive* entities. Contracts and technological installations for instance are passive entities: they are not agents because those entities do not act on their own. Agents behave by interaction with other agents, using inputs from the external world. The external world consists of all relevant parameters that are exogenous: they are not explicitly modelled. Examples are price levels of a commodity market or regulation.

The agents' decisions together shape the system. For instance, for the model built, the list of potential actions includes investment decisions in generation capacity. Electricity producers therefore have the possibility to invest as they please. Because multiple agents have that possibility, the generation portfolio can change: the result of all decisions is that the portfolio emerges as a system property.

Table 6. Properties of agents found in literature.

<i>property</i>	<i>definition</i>	<i>applied?</i>
proactiveness	ability to take the initiative in order to reach goals	yes
situatedness	agent is embedded in its environment and senses and acts on it	yes
reactiveness	ability to react in a timely fashion to changes in the environment	yes
autonomy	ability to control own actions and internal state	yes
social ability	ability to interaction and communication with other agents, sometimes even awareness of other agents	yes
anthromorphy	having human-like attributes, e.g. beliefs and intentions	little
learning	ability to increase performance over time based on previous experience	little
continuity	temporally continuous running process	no
mobility	ability to move around in the simulated physical space, sometimes even between different machines	no
specific purpose	designed to accomplish well-defined tasks	no

### Agents

The main component of ABM's is the agent. A universally accepted definition of an agent lacks (Wooldridge *et al.* 1995; Jennings *et al.* 1996; Schieritz *et al.* 2003). Which properties an entity has to feature in order to deserve to be called an agent is not clear-cut: definitions range from a mere subroutine to a conscious entity (Rocha 1999). An overview of the properties of agents found in literature is given by Schieritz and Milling (2003). Table 6 gives an overview of those properties. The definitions as well as the selection of properties that apply to the agents of the model are listed.

For this thesis this definition is used: “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). An agent thus is a piece of software code in a computer that describes its goals and the ability of taking specific actions. The applied properties of agents, checked in the most right column of Table 6, follow from that definition and imply agents having a number of *components*. Those components are actual parts of agents. The following components, by Weiss (2000) and Bussmann *et al.* (1998), are presented in the used agents:

- 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 (*proactiveness*). The set of goals, are objectives of the agent that it *wants* to accomplish. They could be making profit or minimize environmental impact. Goals of different agents can be different. Agents take decisions to reach these goals. If agents have multiple goals, they need additional information on the relative importance of each goal. For instance, two goals of an agent are maximizing profit and minimizing environmental impact. The needed additional information could be that maximizing profit is twice as important as minimizing environmental impact. Goals can in decisions than used as weight criteria. The goals are static: they do not change over time.

The working memory of an agent is a set of information about itself, called the *state*. The state could for instance contain information on its current age, capital or owned technological installations. The state is dynamic: it changes over time, based on the decisions made by the agent and other agents and changes in the environment.

The social memory is a set of knowledge on the behaviour of the agent and other agents. Past actions and interactions build this memory. Using the information of the social memory in decisions is adaptive behaviour. Agents over time then learn from those past interactions (*learning*). Because all agents make different decisions and have different interactions, the content of their social memory differ. A social memory therefore leads to information asymmetries between agents. Because agents rely on that information, also the beliefs differ (*anthromorphy*). A useful application for a social memory could be that agents keep track of all contracts it has had with according prices. It also can contain information on what other agents are capable of, for instance how many agents are capable of delivery of natural gas. Future models could exploit possibilities in these directions, but for now, the model of this thesis contains limited use of learning and anthromorphy. The modelling environment (see later) gives possibilities for expansion on this topic.

Social engagement rules define the social behaviour of an agent. It contains the abilities an agent has to interact with others or make decisions. Based on interaction with other agents (*social ability*) and input from the environment (*situatedness*) they themselves make decisions (*autonomy*). Decisions can include operational decisions such as the control over power plants, ask for or accept received contracts and pay money or investment decisions in new power plants. Because input from the environment is used, agents respond to exogenous changes (*reactiveness*).

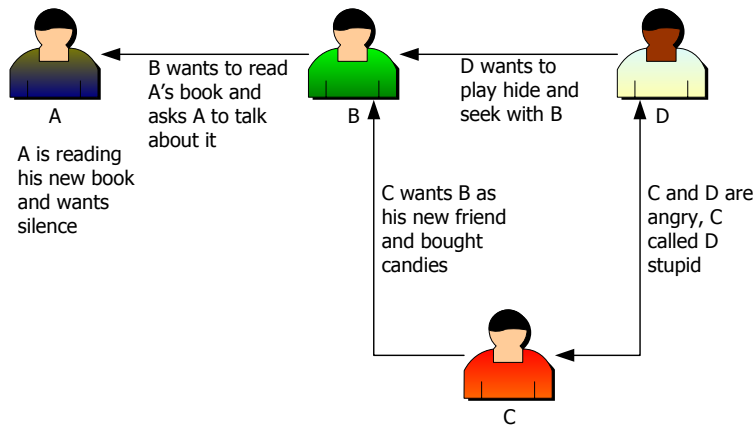
To summarize this, an agent-based model is a simulation of the interaction of a set of agents over time. Agents make decisions based on their goals, exogenous parameters and past interaction with other agents. Only the decisions that agents are allowed to take are centrally defined.

### **Example of an ABM: children's playground**

To elucidate the terminology of ABM, this paragraph presents a short example. Consider some children playing in a playground. If the playground is modelled using the ABM paradigm, children are agents.

Recall the four components of the agents: a set of goals, a working memory, a social memory and a set of rules for social engagement. Goals of these children could differ; possible goals are to ‘be happy’ or to

‘maximize popularity’. The working memory contains characteristics of the agents such as gender, age, name, mood and owned items. The social memory contains data on the games played before and the results of past interaction with other kids: For instance, the response while trying to make friends with them. The rules of social engagements could contain ways of interaction such as to invite to play a certain game, playing a certain game, be friends, but also picking on one of the kids and lying. Figure 18 displays possible relations between four children of such a model in a certain moment in time. This is the models state.



**Figure 18. Children as agents.**

Other parties defined the playing field of the children, the playground. Those parties do not have to be explicit in the model. Local government decided to build that place. The parents made it possible for the children to go and play in this particular playground, because they decided to have children, to live near this playground and to allow the children to play. Those parties are behind the models structure of the playground. They are static during the simulation of this particular model. Other agent-based models of playgrounds could include changes in those areas. For instance, the impact of a new playground on the use of existing playgrounds could be researched. The border of the model thus depends on the research question.

In this simple example, individual behaviour of only four agents (children) already leads to interesting group behaviour. Children C and D have a link to A, but only through B. If C is able to figure that out, he or she might respond to this. Possible strategies could be that C tells negative things to B about A to make sure B will be his friend. Another strategy is to try to be friends with A himself. Without defining group rules, the behaviour and knowledge of individuals make group behaviour emerge over time. This makes unpredictable but realistic results possible, which is one of the advantages of agent-based modelling. Stable or unstable group formations could emerge over time under different circumstances or distributed decision rules. Different initial states and individual rules for agents would give insight in the overall emerging system behaviour. With four children, it could still be deductible, but running models of this kind with hundreds of children might well deliver very interesting results.

These characteristics of agent-based models apply to the model of the agents relevant in the problem of this thesis. In that model, the main critical actors are modelled as electricity producer agents that autonomously invest in generation capacity of their preferred type. Government introduces CET to influence those individual decisions and the emerging portfolio that results from those decisions. All decisions determine the total impact.

### 3.7 Conclusions

The process followed in this thesis consists of a knowledge cycle in which knowledge is built and a simulation cycle in which a simulation model is used to underpin that process.

Agent-based modelling is chosen as modelling paradigm to assess the impact of CET on electricity generation. In that paradigm, decision rules of autonomous *agents* are the central object of study. The

actual impact of CET on the development of electricity generation portfolio is a consequence of the investment and disinvestment decisions of individual and autonomous electricity producers. Therefore, the paradigm fits this problem.

Agents are defined by a set of goals, a memory and a set of rules for interaction. Agents are put in a play garden in which they act. The actual impact of CET is to be found by simulating the interaction of agents – representing critical actors – under a set of external influences.

## **Part II. Model development**





## 4 Model description

### 4.1 Introduction

In the first part of this thesis, the interaction of CET on electricity generation and its portfolio development was explored and criteria were derived to assess its impact. Consecutively, the used modelling paradigm, agent based modelling, was presented. This chapter contains a description of the agent-based model. Implementation and validation issues are dealt with in chapters five and six respectively.

As was said in chapter three, an agent-based model consists of a number of separate components (recall Figure 17). That structure of components is operationalized to develop the model presented in this chapter. Since this is a first attempt to develop such a model, it is based on restrictive assumptions. However, the model is designed to be flexible enough to be extended in the future. In Figure 19, the main components of the model are presented. In addition, Figure 19 gives an overview of the possibilities to extend the model. For that purpose, a distinction is made between components that are fully implemented in the model, components that are in the model, but for which extension is recommended and components that are not yet addressed in the model. More details about the recommended extensions can be found in chapter six, paragraph 6.3. The structure of this chapter originates from the model structure. Since the implementation of the green and orange components is based on a set of assumptions, an overview of the main assumptions under which the model is valid is presented in paragraph 2. Subsequently, the backbone of the model is defined in the sequence of possible actions. Paragraph three discusses those actions. The main input of the model is modelled in scenarios that represent the external world. Paragraph four contains a description of these scenarios. The other inputs, denoted as parameter settings, are discussed together with the agents' definitions in paragraph 5.

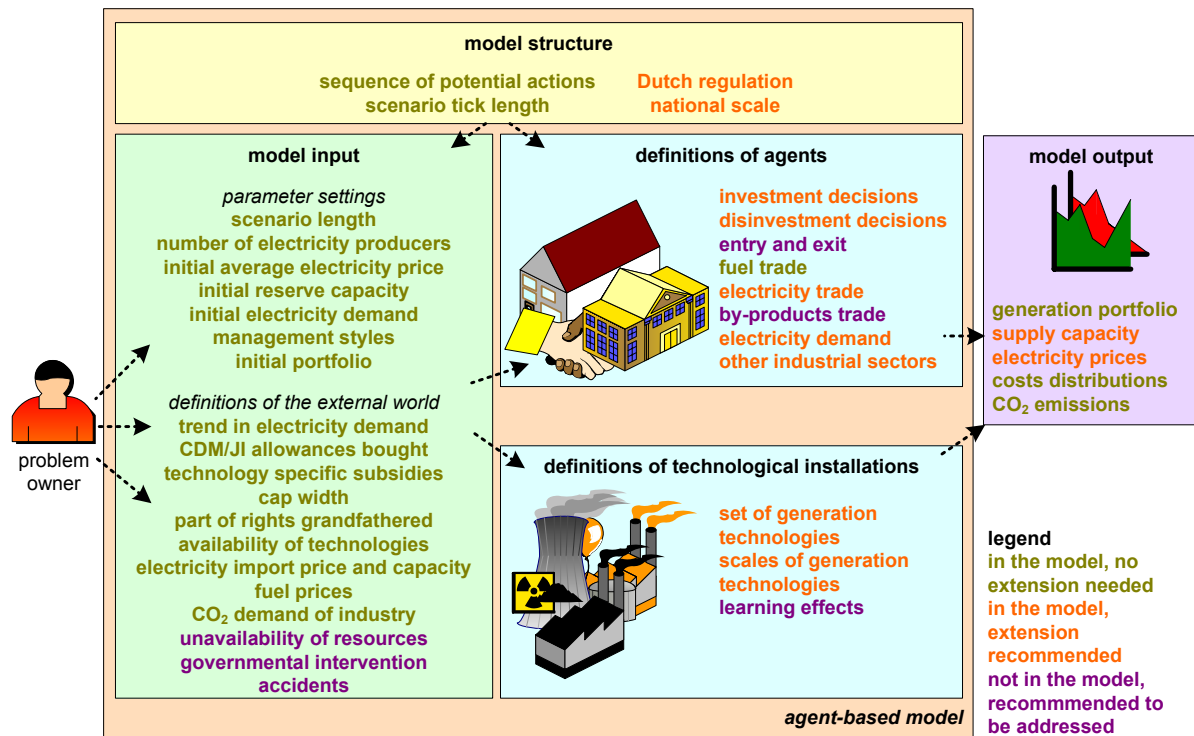


Figure 19. Structured overview of the implemented components and options for extension.

As mentioned, agents in the agent-based paradigm are the central object of study. To grasp the complexity of the system, agents and technological installations are separate types of entities in this model. Agents are active entities, which means that they are capable of performing actions. Technological installations are passive entities, which means that they are owned and controlled, but do not act autonomously. In the fifth paragraph, the definitions of the agents' actions or behaviour are presented as well as the characteristics of those agents. The definitions of the used technological installations are discussed in paragraph six.

The actions and interactions of the agents, together with the technological installations result in a structure on system level. The model does not a priori impose that structure. It is the emerging result of the actions of agents and is dynamic: it can change over time. Remarks on that emerging system structure are discussed in paragraph seven. The chapter ends with conclusions.

## 4.2 Model assumptions

In this paragraph, the delineation is discussed that is used for the model. Because of the explorative nature of this research and the lack of literature on the subject, the assumptions are restrictive. However, the value of agent-based modelling is retained because of the focus that lies on the decision-making of individual electricity producers. This decision-making process is simplified. Although these simplifications, distributed decision-making benefits most from the bottom-up agent-based modelling paradigm. Other parts have to be simplified – sometimes by incorporating top-down aspects – to be able to grasp the complete system. It is the strength of the chosen paradigm and the research approach that both types of aspects can be incorporated in the model. In addition, the model is set up for extension in the future.

### The Netherlands

The first main choice is to look at the Netherlands. Geographical delineation is needed to be able to quantify input data for the model. The main argument that justifies this delineation is that electricity production in the Netherlands is and will probably remain reasonably shielded from the rest of Europe.

This argument rests on two observations. First, transport losses for electricity are significant over longer distances. Second, the inter-connector capacity for transport of electricity between the Netherlands and neighbouring countries is limited to 20% of demand (NMa 2005). Prices for electricity generation in the connecting countries are significantly lower than in the Netherlands. As a consequence of lower electricity generation prices in neighbouring countries, the Netherlands is an importer of electricity and Dutch electricity export is assumed absent. These significantly lower prices lead to *import dominance*: import capacity is always completely used. In the future, investments could be made to increase the inter-connector capacity. However, costs for inter-connector capacity are extremely high. Therefore, it is assumed that import capacity will not increase very rapidly. Electricity is thus a regional good and the Dutch electricity sector is for the largest part separated from the European network.

### Exogenous demand

Most consumers do not change their consumption of electricity to changes in the electricity price (Vries 2004:33). Demand is assumed to be inelastic to the changes in price imposed in the simulations. As a consequence, the impact of CET on the demand for electricity is assumed absent. Therefore, demand for electricity is exogenous to CET and electricity generation. The demand for electricity is described by taking one individual actor representing the entire demand in the Netherlands, based on historical data.

However, in the long run, if prices rise extremely, consumers might switch to less electricity consuming activities. For instance, small end consumers may buy fridges that are significantly more efficient. Large end consumers can switch complete production processes. That feedback is thus *not* directly modelled. The consequences of this feedback are modelled as scenario trends for the demand for electricity.

### Electricity market with perfect competition

Electricity markets can be integrated or decentralized (Hunt 2002). The difference between the market designs is their institutional implementation as to how contracts are formed: whether market operation is integrated with system operation. In an integrated market, all generated electricity is sold to a *pool*.

Consumers can only buy from that pool. Market parties submit their bids in advance. Supply and demand are balanced by the system operator. This means that market operation is integrated with system operation. In contrast, in the decentralized market model, market parties engage in contracts with each other and notify the system operator of their scheduled electricity flows. The functions of scheduling generation, balancing and congestion management are organized separately. Throughout Europe, the decentralized design is currently in place. The integrated design is more common in the USA.

It is assumed that the electricity markets function under perfect competition, in which suppliers' bids are based on variable costs and maximum capacity. The agent-based model coincides with both types of designs. In a decentralized market it is assumed that market players meet so often that prices in a certain period converge to an equal level for all market players. As a consequence, the neoclassical outcome of the decentralized market is that the power plants with the highest variable costs do not run and the most expensive running unit determines the price (EIA 2002). In an integrated market, the market operator clears the market by the intersection of supply and demand curve. A single market price is the result that again equals the most expensive running unit.

The integrated and decentralized market designs differ in the institutional implementation, but under perfect competition, both the decentralized and the integrated market designs have the same outcomes. Therefore, both market designs coincide with the model.

### **Market for CO<sub>2</sub> rights**

The market for CO<sub>2</sub> rights, in this thesis is denoted as the 'CO<sub>2</sub> market', is assumed to be an aggregate market in which trade and price forming takes place once a year. That process is characterised by perfect competition: prices are based on the demand and supply for rights. Demand is determined by the actual emissions and supply is based on the cap of rights. Opportunity costs for grandfathered rights are taken into account.

The distribution of rights among the involved sectors can change over time. That is modelled as trends for change in the cap for the rights for the electricity sector. The cap on the rights for the other sectors are translated to trends in the demand of those sectors of rights *beyond* their cap.

Agents can always buy emission rights on the CO<sub>2</sub> market. If the demand for rights grows beyond the imposed cap, it in reality would translate to import of rights or to executing projects returning JI or CDM allowances.

Data needed for modelling CET comes from the configuration of the first period (2005-2008). Other information is not yet available. The foreseeable changes on a national scale from 2008 are minor.

### **Homogeneous and transparent world market**

A world market is assumed to exist that is homogeneous and transparent for all market players. All fuels are assumed to come from this world market. Every player can buy fuels against the same world market price. Import of electricity also comes from that world market, limited by the inter-connector capacity.

As for CO<sub>2</sub> rights, availability of fuels is assumed to be unlimited. Fuel prices are modelled as exogenous variables. Reserves of most fuels are large enough to cover supply during the simulation. Only the proven reserves for the natural gas in terms of years are smaller than the simulation length. In reality, high prices for natural gas lead to more affordable production techniques. In addition, technological developments under higher prices will probably lead to an increase in the available resources by conversion from other fuels. Consequently, the resources for natural gas are not limited within the time-scale of the simulation.

It is assumed that transport costs are included in the price for any commodity sold on the world market. For electricity, the main costs for electricity are the generation costs and transport is less significant. For fuels, transport costs are included in the prices used.

Scarcity of a commodity generally leads to higher prices. However, the use of fuels in the Netherlands does not directly affect prices on a world scale. The first reason is that price forming for fuels is a very

complex process that is shaped, besides by demand and supply, by political decisions. Second, the Netherlands are small compared to the world market. Therefore, changes in prices are assumed to be independent from outcomes of the model. They follow specific trends grasped in scenarios representing possible world-scale developments.

### Simplified power plants

Electricity producers can invest in a limited set of power plant types. This set is based on the types used in The Netherlands. This choice limits the data needed to create a working model. In addition, the set of power plant types that can be invested in is constant. The only technological innovation modelled is the introduction of clean coal, because that is the most promising technological innovation especially for the Netherlands. Moreover, it is assumed that the electricity producing companies have equal technological knowledge and can acquire the same types of power plants.

All combined heat and power and trigeneration plants are assumed to be ‘electricity-driven’: they run when demand for electricity exists. Selling co-produced heat and/or chemical products is not modelled. Therefore, all plants are modelled as regular power plants. In this model, selling electricity is the main goal for the owners of these plants. In future models, selling heat and chemical products could be modelled as well. Other models on that topic are being developed (Nikolic *et al.* 2007). Opportunities for coupling those models can be exploited in a later stage. Interaction with the chemical industry is therefore not modelled and, as mentioned above, the results do not account for the revenue generated by selling heat or chemical products.

It is assumed that power plants are capable of running at full capacity during the complete lifetime. In addition, there are no limits to the possible locations for power plants. However, an exception is made to both assumptions for wind farms. Wind farms depend on wind speeds for their output. The average output of wind farms is much lower than the capacity. Wind farms cannot be placed close to each other. Both are taken into account. For more information on the properties of power plants and data sources, see Appendix B.

Construction costs only depend on the type and size of the power plant. Connectivity to a suitable power grid is assumed to exist. Power plants can directly connect to the electricity consuming technological installation.

### Electricity producers

It is assumed that no new players enter the market. Additionally, market players do not merge or leave. This means that the *number* of electricity producers is static. Capital needed for investments is assumed available. Electricity producers have equal access to the needed capital; a capital market is therefore not modelled. All prices are valued against current price levels. Inflation and interest rates are assumed constant and equal; they are not modelled explicitly. This functionality may be added to the model in the future.

Investment and disinvestment decisions are simplified. Electricity producers only have information on their own plans and construction activities. Electricity producers all autonomously make investment and disinvestment decisions. Investment decisions are based on a multi-criteria analysis. The set of criteria is equal for all electricity producers, but the producers weigh the criteria differently. Governments’ policy also affects some of the weights for the criteria.

## 4.3 The model backbone: sequence of possible actions of agents

The backbone of agent-based models connects all components, such as agents to scenarios. An agent-based simulation is composed of agents executing actions. The backbone of the model, described in this paragraph, is a sequence of *possible* actions for agents. The model does not *prescribe* actions, but gives opportunities for individual agents to act at specific moments. All actions are modelled to occur once per year. The main time step or tick in the model is therefore one year. The simulation length for the runs reported is 75 years, or 75 model ticks.

The backbone of the model also initializes a simulation run. Before the first tick, a start-up set of six electricity producers is made. The power plants they own are based on the demand and portfolio structure of the Dutch situation of 2004. Other agents are set up as well, namely the consumer, environment, government, world market, CO<sub>2</sub> market, electricity market and other industry. Some of those agents have technological installations. See Figure 24 for an overview of the agents and technological installations in the model.

After initialization, the simulation run starts. Each tick, all agents may execute the following four actions:

1. trade electricity
2. acquire the resources needed for the contracted supply of electricity
3. acquire CO<sub>2</sub> rights
4. make investment and disinvestment decisions

A short introduction of the four actions is presented here. Details can be found in the definitions of the agents in paragraph 4.5. The first three actions are operational actions. First, electricity trade is facilitated by the electricity market. It couples supply and demand in contracts with calculated amounts and prices. In the second step, each agent acquires resources needed to act up to their (new) contracts. That implies that electricity producers will try to buy the fuels needed for electricity production. It also means that the environment will accept all by-products and emissions. In the third step, agents have the opportunity to acquire CO<sub>2</sub> rights if they need them. Electricity producers acquire them, as they need to cover the emission caused by electricity generation. The industry agent buys the demand of rights that the other sectors have beyond their cap. The last action contains strategic, long-term decisions. All electricity producers are given the opportunity to invest in new power plants, to be able to meet rising demand or to replace old power plants. In addition, producers may disinvest in current power plants that are too old or unprofitable.

The model is configured such that the agents *all* have to finish the first action before any agent can proceed to the second action. After all agents finished the last action, a simulated year has passed. The sequence is repeated until the simulation length is reached. It must be noted that only the *opportunities* of the actions are determined by this structure. The actions themselves reside in the agents, discussed in paragraph 4.5. But first, the external world imposed on those agents is discussed.

#### 4.4 Definitions of the external world: scenario development

The world in which the agents ‘do business’ is modelled as scenarios. In other words, the scenario is the ‘playing field’ of the agents. Environment scenarios represent the range of possible futures that can be expected (Enserink *et al.* 2002). Development of those scenarios is done in three steps. First, relevant factors are defined. Factors of relevance are uncertain in the future and have a potential influence. Only factors that cannot be influenced by electricity companies will be used. The other relevant factors should be in the model already. Second, driving forces are formulated. Driving forces are very generic, abstract factors. The driving forces have an influence on relevant factors that define the future environment of the agents. In the third step, a workable number of scenarios are modelled based on these driving forces. All driving forces become axes of the scenario space. Consequently, the scenario space consists of all possible futures that these driving forces could form. Scenarios are selected as static locations in the scenario space.

##### Driving forces and influenced factors

The driving forces are world economy growth, environment mindedness and external limitations. Relevant operationalized factors are formulated.

Table 7 presents an overview of the driving forces and the influenced factors. Indications of the uncertainty and influence of factors are given. More plus signs mean larger uncertainty or influence. A discussion follows of the driving forces and the factors they influence.

**Table 7. Relevant factors and driving forces for scenario development.**

<i>driving forces</i>	<i>factors influenced</i>	<i>uncertainty</i>	<i>influence</i>
world economy growth	aggregate electricity demand	+	+
	average margin in electricity bids	+	+
	CO <sub>2</sub> right demand of other industry	+	+
	fuel prices	+	+
environment mindedness	amount of JI/CDM allowances bought	+	+
	technology specific subsidies	+	+
external limitations	cap width	++	++
	parts of rights grandfathered	+	++
	electricity import price	+	+
	inter-connector capacity	+	+/-
	types of power plants available	+	+

#### *World economy growth*

It is assumed that the world economy growth cannot be directly influenced. It is a global development with large consequences for the electricity sector. The demand for electricity and prices on electricity and fuel markets are in continuous change.

- The demand for electricity is the main driver for electricity generation and for investments in new power plants. Uncertainty resides in the long-term growth in population and energy use per capita.
- An average margin in supply bids on the electricity market is used to model strategic behaviour of electricity producers. Possibilities for strategic behaviour is uncertain due to regulatory uncertainty. Since strategic behaviour affects electricity prices, it is relevant as scenario parameter.
- The distribution of CO<sub>2</sub> emission rights over the different sectors is relevant, because it determines the cap of rights for the electricity sector and prices on the market for emission rights. Uncertainty is large, since historic data on prices are only available since 2005.
- Fuel prices are relevant, because they are the main variable cost factor for the production of electricity. Political aspects of price forming cause fuel prices to be uncertain.

#### *Environment mindedness*

Environment mindedness is a global wish towards more sustainable use of natural resources and the preservation of the environment for future generations. Consumers' future drive for environmental protection is uncertain, since this often changed in the past decades. The consumers' wish of more environment minded policy and behaviour of government and companies has influence on the political agenda. Therefore, it influences the environmental policy measures taken by government.

- The amounts of JI/CDM allowances bought by government are uncertain. It is relevant for the total amount of allowances on the CO<sub>2</sub> market. It is without doubt that this amount changes with the election cycle.
- That political process also influences subsidies that provided for the installation of environmentally friendly power plants. Those subsidies have a direct influence on the costs for power plant types.

#### *External limitations*

The last driving factor, external limitations, is defined as the amount to which external regulation impose limits to the development of capacity in the electricity sector.

- The cap on the amount of rights in the CO<sub>2</sub> market influences several power plant types. Uncertainty of this cap is large, because the cap for 2008-2011 is still not completely known. No decisions are made yet for post-Kyoto.
- The part of the rights that are grandfathered to emitting parties is uncertain as well. For the first period (2005-2007) a minimum of 95% is regulated and this is 90% for the second period (2008-2011). However, nothing is known on grandfathering after that period. Less grandfathered rights means that more rights are bought via a market or auctions.

- The electricity import price and capacity are relevant because of import dominance. Foreign prices could change. Investments in inter-connector capacity can lead to increase in import.
- The last factor determined by external limitations is the set of power plant types available. Future options and their costs remain uncertain. The innovative concept clean coal is modelled. Recall that a clean coal power plant is a coal power plant with underground CO<sub>2</sub> storage.

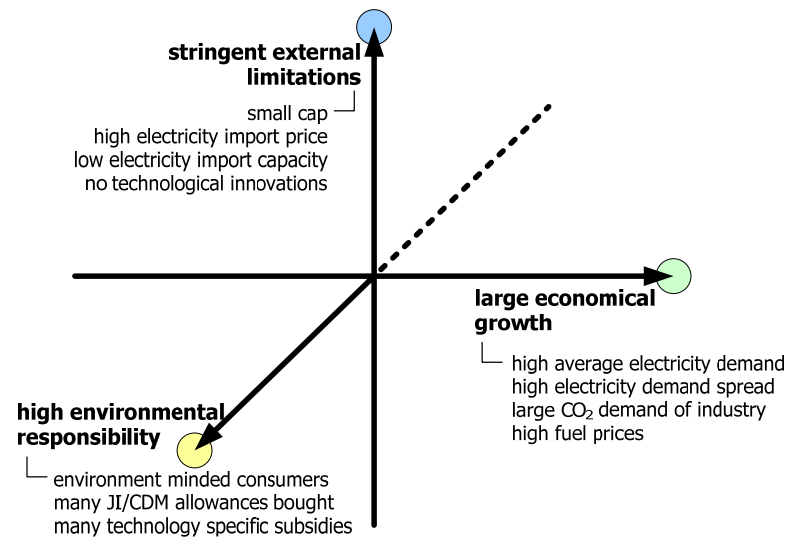


Figure 20. Scenario space.

### Scenario selection

Figure 20 displays this scenario space. Each location in the space is one possible scenario. As mentioned above, the axes of the scenario space are the earlier presented driving forces. Specific locations in the scenario space define possible future trends. The location in the scenario space is static. Because this thesis is explorative nature, it is of interest to find the complete range of system behaviour that can be expected. Therefore, the scenarios selected are extreme in the sense that they are placed at the extremes of the axes. To get the complete range of system behaviour, all possible combinations of extreme values on the axes are selected. Because the scenario space has three axes, the set of extremes can be viewed as the corner points of a cube.

Figure 21 presents the scenario space with all scenarios as numbered circles. The axes are not presented in the figure for reasons of readability. All scenarios on the yellow side (1, 2, 3 and 4) have high environmental responsibility, the others (5, 6, 7 and 8) have low environmental responsibility. All scenarios on the blue side (1, 3, 5 and 7) have stringent limitations, the others (2, 4, 6, and 8) have low external limitations. The scenarios on the green side (3, 4, 7 and 8) have large economic growth and the others (1, 2, 5 and 6) have small economic growth. An additional scenario is placed at the centre of all axes, and is called scenario 0. This scenario is used as 'average' scenario for the sensitivity analysis (see chapter six).

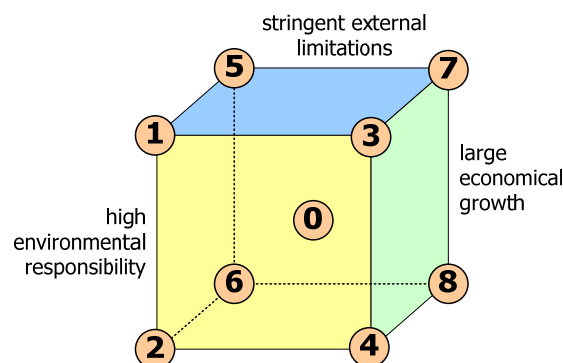


Figure 21. Scenario selection.

The scenarios are completed by defining trends and initial values for all factors (see Table 8). Discussion of those levels and the data sources can be found in Appendix C.

**Table 8. Scenario data values and trends (see Appendix C for data sources).**

<i>driving forces</i>	<i>factors influenced</i>	<i>initial value</i>	<i>high trend</i>	<i>medium trend</i>	<i>low trend</i>
world economy growth	aggregate electricity demand	106 TWh	+ 4%/year	+ 2%/year	+ 0%/year
	average margins in supply bids	<i>constant</i>	15%	10%	5%
	CO <sub>2</sub> right demand of other industry	<i>constant</i>	10 Mton	5 Mton	0 Mton
	natural gas price	0.144 €/m <sup>3</sup>	+ 6%/year	+ 4%/year	+ 2%/year
	coal price	52.6 €/ton	+ 3%/year	+ 2%/year	+ 1%/year
	uranium price	40 €/kg	+ 5%/year	+ 3%/year	+ 1%/year
	bio-fuel price	66 €/ton	+ 2%/year	+ 1%/year	+ 0%/year
environment mindedness	amount of JI/CDM allowances bought	<i>constant</i>	10 Mton/year	5 Mton/year	0 Mton/year
	technology specific subsidies	<i>constant</i>	100 €/MW	50 €/MW	0 €/MW
external limitations	cap width	50 Mton	- 2%/year	- 1%/year	+ 0%/year
	part of rights grandfathered	<i>constant</i>	70%	80%	90%
	electricity import price	15 €/MWh	+ 2%/year	+ 1%/year	+ 0%/year
	inter-connector capacity	20 TWh	+ 0%/year	+ 1%/year	+ 2%/year
	types of power plants available	<i>constant</i>	no clean coal	clean coal	clean coal

## 4.5 Definitions of agents

The main components of an agent-based model are the agents. This paragraph contains definitions of the agents. Two types of agents are distinguished: actors and markets. Actors and markets can make intelligent decisions; they are autonomous and active. The actors are electricity companies, government, industry and consumers. Markets facilitate trade. The markets in the model are the electricity market, a market for CO<sub>2</sub> rights and a world commodity market.

By choice of definition, technological installations such as power plants are not considered agents, because they do not act autonomously. Technological installations do not take decisions and are treated as black boxes, characterised by their inputs and outputs. The agent that owns a technological installation operates and controls it. The knowledge and behaviour needed for that is thus modelled in the agent. In reality, some technological installations can have physically integrated decision-making. However, in this model all behaviour is in the agents.

Recall the discussion of chapter three, where it was concluded that agents are modelled by the following four parts. The first is a set of goals the agent tries to achieve. The working memory is a set of properties about the agent. The social memory consists of information about other agents. Finally, the set of rules of social engagement defines the behaviour of agents. In their behaviour, agents try to achieve their goal. The agent uses the information in the working memory and social memory to accomplish that goal. Table 9 summarizes the presentation of the four parts of the agents. The rest of this paragraph contains a presentation of definitions of the agents. That description mainly consists of logic, but some mathematical formulas are used. The formulas are presented as such whereas the logic is presented in sentences.

**Table 9. Summary of the definitions of agents.**

<i>agent</i>	<i>goals</i>	<i>working memory</i>	<i>social memory</i>	<i>rules for social engagement</i>
electricity producer	maximize profit by selling electricity	capital management style and market position set of owned power plants profitability per power plant	fuel prices electricity price CO <sub>2</sub> right price grandfathered rights	operate power plants sell electricity buy fuels buy CO <sub>2</sub> rights (dis)invest in power plants
government	effective CO <sub>2</sub> reduction	capital cap on CO <sub>2</sub> rights part of CO <sub>2</sub> rights grandfathered subsidy height	<i>none</i>	buy JI/CDM allowances provide subsidies provide CO <sub>2</sub> rights



industry	maximize profit by selling chemical products	nuclear fear space factor capital demand CO <sub>2</sub> rights	<i>none</i>	buy CO <sub>2</sub> rights operate chemical installation
consumer	experience pleasure or generate profit by consuming electricity	capital electricity demand	<i>none</i>	buy electricity operate consuming installation
environment world market	receive emissions sell fuels and imported electricity	CO <sub>2</sub> emissions capital fuel prices set of owned delivery installations	<i>none</i> <i>none</i>	take up emissions sell fuels sell imported electricity operate delivery installations
electricity market	facilitate electricity trade	electricity price per installation electricity output per installation	<i>none</i>	ask for contracts with bids to sell and buy electricity calculate electricity prices and electricity outputs per installation
CO <sub>2</sub> market	facilitate CO <sub>2</sub> right trade	CO <sub>2</sub> price	<i>none</i>	deal with import dominance determine CO <sub>2</sub> market price sell CO <sub>2</sub> rights

### Electricity producer

Electricity producers own and operate power plants. The main goal is to maximize profit by generating and selling electricity.

As mentioned before, electricity producers differ in their perception and priorities. To grasp the differences in the decisions of electricity producers, the concept *management style and market position* is introduced. The working memory of electricity producers mainly comprises the parameters determining that management style and market position. The management style and market position is defined as a collection of parameters with values, that the agent uses in the actions and decisions. All electricity producers have a unique management style and market position. They all have the same parameters, but the values differ. For six electricity producers a set of values on these parameters are presented. As a consequence, the actions are different per electricity producer.

Table 10 presents an overview of the management style and market position parameters and the values. Appendix D gives a discussion on the parameters and the values given. The parameters are all discussed below.

**Table 10. Parameter values of management styles and market positions of electricity producers.**

<i>management style and market position parameter of electricity producer</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>	<i>6</i>
margins in bids (% of average margin)	125	125	100	100	75	75
years of consecutive losses before disinvestment	5	9	7	9	5	7
maximum concurrent investments	10	8	6	10	8	6
demand/supply ratio barrier for investing	0.70	0.83	0.95	0.83	0.70	0.95
economics factor	5	5	5	3	3	3
environmentally friendliness factor	0	1	2	0	1	2
conservativeness factor	1	2	1	2	1	2
nuclear fear factor	4	4	2	2	4	4

The social memory stores market prices for fuels, electricity and CO<sub>2</sub> rights. In addition, the amount of received grandfathered rights is stored. Finally, the profitability is stored per power plant that the agent owns.

In the set of rules for social engagement, the electricity producer distinguishes between operational actions and strategic actions.

### Operational actions

One of the main operational actions is to sell electricity by the use of contracts. Contracts are used for all trade in the model. Those contracts contain information about the traded object or flow of commodity, the buyer and seller. The duration of all contracts is one year. See paragraph 5.2 for more information on the definition of contracts in the model. Electricity producers can make contracts for all owned power plants. The amount offered is the maximum capacity. The price offered to sell the electricity is calculated to cover the *expected* variable costs for the production of electricity, including a margin. The following formula is used:

$$\text{bid [€/MWh]} = (\text{fuel costs} + \text{other operational costs} + \text{CO}_2 \text{ costs}) \times \left( 1 + \frac{\text{margin} \times \text{scenario average margin}}{100} \right) \quad (4)$$

The used figures are the expected fuel costs, expected costs for needed CO<sub>2</sub> rights and the expected other operational costs. Because the all those costs rise linear with an increase in production, the variable costs are assumed constant over capacity. The following formula is used for the estimation of the CO<sub>2</sub> costs:

$$\text{CO}_2 \text{ costs [€/MWh]} = \text{CO}_2 \text{ price [€/ton]} \times \text{CO}_2 \text{ intensity [ton/MWh]} \times (1 - \text{part grandfathered}) \quad (5)$$

Electricity producers estimate costs for CO<sub>2</sub> rights on basis of the price, known from last year and the part of the rights that was grandfathered in that year. In the model, no costs are counted for grandfathered rights, because that is assumed by policy markers. However, it is observed that electricity producers in reality take the opportunity costs of grandfathered rights into account. Therefore, in chapter seven, those two methods are compared.

In the estimation, it is assumed that the grandfathered *part*, and the CO<sub>2</sub> price are equal to last year. Additionally, the CO<sub>2</sub>-intensity of the production process is used to calculate the expected CO<sub>2</sub> costs. To model strategic behaviour, a margin is added to the bid, based on the management style and market position of the agent. The average margin for all producers is a scenario parameter to indicate the possibility for strategic behaviour.

Another operational action that electricity producers undertake is buying resources needed to produce the electricity they contracted earlier. Based on the contracts signed to sell electricity from specific power plants, actions are taken to buy the needed fuels. The agent asks to all other agents for contracts for the needed resources and makes the necessary physical connections to receive them. The electricity producer is also a seller of the by-products of the electricity production processes. By-products are sold to the highest bidder. Most of the by-products, such as heat and CO<sub>2</sub>, are however unwanted. To be able to check mass balances, the physical flows to the environment are modelled as well. See the description of the environment for more details.

Electricity producers are modelled to pay the operational costs (other than fuel and CO<sub>2</sub> costs) once a year. The costs are made inside the company. Therefore, no transactions with other agents in the model take place. These costs are only based on the electricity output of power plants.

Electricity producers can acquire CO<sub>2</sub> rights. This is different from asking for the contracts for fuels and electricity, because CO<sub>2</sub> rights are intangible. The rights are not transported and therefore do not need any physical connection. The electricity producer calculates the amount of rights needed by taking the actual emission of the power plants owned by the producer. Contracts are asked for the needed rights and the cheapest options are used. Because the government and the CO<sub>2</sub> market will respond with a contract, this means that first the grandfathered rights are used and if that amount is insufficient, rights are bought on the market. The payment(s) are made to the selling agent(s) and all other contracts are removed.

### Investment decisions

An investment decision has two separate parts:

- the decision whether a new power plant has to be invested in
- the choice of technology

The first part is the decision whether an investment has to be made. Electricity producers invest for two reasons: an existing power plant has to be replaced, or to prevent shortage of supply capacity. If the physical lifetime of power plants owned by an electricity producer is no longer than 3 years, it is assumed that the electricity producer will replace the power plant with 90% chance. In addition, an investment is made if the demand for electricity comes close to the total supply capacity. The criterion is denoted as the *demand supply barrier* and is defined as:

$$\text{demand supply barrier [-]} = \text{electricity demand [MWh/year]} / \text{electricity generation capacity [MWh/year]} \quad (6)$$

In other words, the fraction of demand over supply functions as a trigger to invest. The triggering value differs per producer and is defined in the management style and market position parameter called demand supply barrier. A lower value for this parameter means a more risk-taking electricity producer. That producer invests when a shortage in supply capacity is not yet apparent. The total concurrent number of power plants that electricity producers invest in is limited. This is also part of the agents' management style and market position, with the parameter *maximum concurrent investments*.

The second part entails the selection of the best option. An electricity producer selects the best generation technology by a multi-criteria analysis. The procedure starts by making a list of the alternative technologies available. The sizes of the proposed plants are random, within plausible ranges per power plant type. More on those ranges and other properties of power plants are discussed later this chapter and can be found in Appendix B.

After that, the producer agent calculates the scores of all potential power plants on a set of criteria. The criteria are the same for all electricity producers. The criteria are economics, environmentally friendliness, conservativeness, nuclear fear and spatial consumptions. Recall that the weighing of the criteria differs between agents.

The first criterion indicates the expected profitability of a power plant. The following formulas are used:

$$\text{yearly profit [€/year]} = \frac{\text{expected lifetime revenue} - \text{expected lifetime costs}}{\text{lifetime}} \quad (7)$$

with  $\begin{cases} \text{expected lifetime revenue} = \text{lifetime} \times \text{capacity} \times \text{electricity price} + \text{subsidy} \\ \text{expected lifetime costs} = \text{investment costs} + \text{lifetime} \times \text{capacity} \times \text{variable costs} \end{cases}$

Note that the unit of the capacity of a power plant in this thesis is MWh/year. The producer calculates the expected lifetime revenue, based on the lifetime, the capacity and the current price of electricity. In addition, subsidies are used in the calculation. As mentioned earlier, the government provides subsidies for the investment in environmentally friendly generation technologies, based on the scenario. The expected lifetime costs constitute investment and variable costs. The expected variable costs include CO<sub>2</sub> costs, fuel costs and other operational costs and correspond with the ones mentioned earlier this section (see equation (4)). As said, with these figures, the agent calculates the expected yearly profit, a figure that by definition is comparable between alternatives with different lifetimes. In this model, calculations do not incorporate interest rates or costs for capital and assumes that prices for fuels, electricity and CO<sub>2</sub> rights will remain constant at the current price levels. However, in the future, that can be incorporated.

Second, the environmentally friendliness criterion calculates the expected yearly CO<sub>2</sub> emission of a power plant as indicator of the environment friendliness of the observed power plant. Because some electricity producers state they are environmentally minded, this is included in the decision-making of producer agents.

Third, the conservativeness criterion calculates how much of the power plants are already in the market as an indicator of how conservative the behaviour would be when this power plant was selected. Parties that do take fewer risks than others are assumed to make more conservative choices than others.

Fourth, the nuclear fear criterion checks whether it is a nuclear power plant. Government, but also private parties can have a policy against nuclear power plants. This criterion is an indicator if a power plant is nuclear.

Finally, the spatial consumption criterion calculates how much space each power plant would consume. The score on this criterion includes both the amount of possible sites that exist for new power plants of the different types and the amount of space they use.

All potential new power plants are valued on the criteria mentioned above. The scores fill the matrix  $S$ :

$$S = \begin{bmatrix} s_{alt.1,cri.1} & \cdots & s_{alt.1,cri.m} \\ \vdots & \ddots & \vdots \\ s_{alt.n,cri.1} & \cdots & s_{alt.n,cri.m} \end{bmatrix} \quad (8)$$

The score  $s_{alt.n,cri.m}$  is the score of the alternative  $n$  on the criteria  $m$ . The agent normalizes the scores between zero and one, where zero is the worst of all and one is the best of all. For the criteria where lower figures are 'better', figures are reversed.

The matrix  $W$  is constructed that contains the weight factors on the criteria:

$$W = \begin{bmatrix} w_{cri.1} \\ \vdots \\ w_{cri.m} \end{bmatrix} \quad (9)$$

In this matrix,  $w_{cri.m}$  is the weight factor on criterion  $m$ . The management style and market position of the agent together with scenario data determine that set of factors. This makes the decision unique per electricity producer and per scenario. The weight factors are constant per electricity producer per scenario. The weight factors for the first three criteria are equal to the equivalent parameters of the management style and market position: The economics factor weighs the economics criterion, the environmentally friendliness factor weighs the environmentally friendliness criterion and the conservativeness factor weighs the conservativeness criterion. In contrast to the first three factors, nuclear fear of specific producers is not only based on the individual management style and market position. National policy that is set by government has large influence. Therefore, the government has a national fear for nuclear factor. The weight factor is the multiplication of the individual parameter and the national factor for nuclear fear. The weight factor for the spatial consumption criterion is only based on the available space for industrial activities. That factor is equal for all electricity producers and is set the government.

The normalized scores are weighed to a set of weight factors. This is done by calculating matrix  $R$ , the product of  $S$  and  $W$ .

$$R = S \times W = \begin{bmatrix} s_{alt.1,cri.1} & \cdots & s_{alt.1,cri.m} \\ \vdots & \ddots & \vdots \\ s_{alt.n,cri.1} & \cdots & s_{alt.n,cri.m} \end{bmatrix} \begin{bmatrix} w_{cri.1} \\ \vdots \\ w_{cri.m} \end{bmatrix} = \begin{bmatrix} r_{alt.1} \\ \vdots \\ r_{alt.n} \end{bmatrix} \quad (10)$$

In this matrix,  $r_{alt.n}$  is the result for alternative  $n$ . The power plant with the highest value is selected and that one is scheduled for construction. The investment costs are paid and the construction starts. After the construction period has passed, the power plant is operational for electricity production.

#### *Disinvestment decisions*

As for investment decisions, two reasons for disinvestment exist. The first reason of an electricity producer to disinvest a power plant is when the power plant reaches its technical lifetime. The technical lifetime of power plants is one of the main characteristics of the power plants. More information on these characteristics can be found later this chapter. Second, disinvestment may happen, when the power plant

is not profitable enough to exploit it. Electricity producers keep track of all costs and revenue per power plant they own. In this model, power plants can make losses. Electricity producers can bid below marginal costs, if real prices for resources are higher than expected. Electricity producers adjust their biddings each period. However, the main time step in the model is one year. Consequently, in the model losses are significantly larger than they would be in reality. If the producer notices that a power plant is causing losses during a number of consecutive years, he will disinvest the power plant. The amount of consecutive years after before disinvestment is unique for electricity producers. The management style and market position parameter *maximum years of losses* defines that number of years and varies between 5 and 9 years. As mentioned, losses in the model are larger than in reality. To account for that, electricity producers only disinvest after a relatively large number of years.

### Government

The goal of the government is to reduce CO<sub>2</sub> emissions effectively. Next to achieving that goal, he has several roles in this model:

- set regulation against nuclear power generation and the number of sites available for power plants
- buy additional foreign allowances through Joint Implementation and or the Clean Development Mechanism
- give specific subsidies for environmentally friendly power plants
- define allocation plans, detailing which rights are allocated to each carbon dioxide emitting party

One agent called government fulfils all these roles. Regulation of the electricity sector, such as the liberalised setting is assumed static and is translated in the structure of the model. Because the geographical delineation, this regulation can be seen as static. However, policy for nuclear fear is modelled as the national fear factor. In addition, government regulates the locations for new power plants in zoning schemes. The amount of spaces available is modelled in the national space factor. Electricity producers used that factor in their investment decisions.

When the government decides to buy extra JI/CDM allowances on the world market by provisioning the execution of JI/CDM projects, they are able to increase supply side on the market for CO<sub>2</sub> rights. The scenario, discussed in the previous paragraph, defines the amounts of additional foreign allowances bought. Government makes that decision implicitly and costs for those measures are not in the model. This can be included in a later stage to better observe the social costs and benefits of this measure.

Subsidies make investing in specific environmentally friendly technologies more attractive. Government decides to grant subsidies based on the type of power plant. Only non-nuclear power plants without CO<sub>2</sub> emission qualify for subsidies. Subsidies lower the investment costs of those power plants. The heights of subsidies are determined in the scenarios.

The government defines the allocation plans. The allocation plan states what amounts of free rights the owner of each installation receives. The government makes the needed calculations when agents ask for CO<sub>2</sub> rights. The government in this model only give rights to electricity producers, because only the allocation plans of the electricity sector are modelled. The other sectors are modelled as the industry agent (see below). The total cap for the electricity sector is in reality the outcome of negotiations between the sector organizations and the government. In this model, the scenarios define the cap and its change.

The government supplies CO<sub>2</sub> rights with contracts. Because government only provides grandfathered rights – the other rights are for sale on the CO<sub>2</sub> market – electricity producers acquire these rights at no cost. The government calculates the amount of rights for a specific electricity producer on basis of the total emission of CO<sub>2</sub> this year, the cap, the amount of CDM and JI allowances that are bought, the percentage of the total rights that are grandfathered and the emission of the agent asking for the contract. The calculation is made in two steps. First, a formula is used to calculate what part of the total emission caused by electricity generation will be grandfathered.

$$\text{part of market grandfathered [-]} = \frac{\% \text{ total rights grandfathered}}{100} \times \frac{\text{total cap [ton/year]}}{\text{total emission [ton/year]}} \quad (11)$$

It calculates the total cap (the domestic cap and the acquired CDM and JI allowances) and by dividing by the total CO<sub>2</sub> emission, the ratio of total rights that are available over the demand for rights is calculated. The right term thus defines the supply and demand ratio for emission rights. But the government can decide not to grandfather all the rights within the cap. The other rights are sold on the market. The part of the rights that are grandfathered, defined by the scenarios, is therefore multiplied by the first figure.

Second, a formula is used to calculate the grandfathered rights for a specific electricity producer.

$$\text{grandfathered rights [ton]} = \text{emission of this agent [ton]} \times \text{part of market grandfathered [-]} \quad (12)$$

The emission of an agent multiplied by the part of the market that is grandfathered gives the amount of rights that the government supplies to the agent that asked for a specific amount of rights.

### Industry

A large number of companies of other industrial sectors than electricity production emit CO<sub>2</sub> and are obliged to own emission rights for their activities. Their goal is to maximize their profit by selling chemical products. Because those sectors are outside the system, their production processes are not in the model. A single industry agent represents all those companies. This agent operates their chemical installations and can buy CO<sub>2</sub> rights.

The model does not include the allocation schemes nor technological developments of those sectors. The allocation schemes per sector are the outcome of the ongoing negotiation process of those sectors with the government. Scarcity in those schemes can therefore change over time. An increase in scarcity leads to more demand of those sectors for CO<sub>2</sub> rights on the CO<sub>2</sub> market. Technological developments can also lead to change in emissions and the according demand for emission rights. This means that the demand of industrial sectors for rights on the CO<sub>2</sub> market is affected.

These two processes both lead to change in the demand for CO<sub>2</sub> rights on the market. Therefore, these industrial sectors are included as one aggregate industry agent that has a certain demand for CO<sub>2</sub> rights. The level of demand is a consequence of the scenario. In a later stage, an extension to aggregate agents can be introduced that represent the different sub sectors of the industry.

The process of acquiring the needed CO<sub>2</sub> rights on the market is similar to that of electricity producers.

### Consumer

The consumer has as goal to experience pleasure or generate profit by consuming electricity. The consumer agent therefore buys electricity and operates its consuming installations.

Because CET is assumed not to affect demand for electricity and demand is inelastic to changes in price, consumption of electricity follows the exogenous demand trends defined in the scenarios. An aggregate consumer agent represents all consumers of electricity. The electricity market, described below, contacts the consumer for a contract. The electricity is bought from the electricity market. The electricity market facilitates the arrangements with the producers of electricity. The electricity transmission and distribution grids are not modelled, because this is not within the system border. The consumer assumes that he can physically connect his installation with all power plants. Costs for that are assumed to be included in the price.

### Environment

The environment is represented as an agent, to be able to visualise the physical flows to the environment. Therefore, its goal is to receive emissions. The environment consumes all emissions of CO<sub>2</sub>, water flows, waste heat flows and other exhaust flows.

The environment allows other agents to deliver him products by contracting them at no cost. All unwanted products can be ‘sold’ to the environment. The other agents therefore use the environment as sink for products that they cannot sell. Because the environment is modelled as such, all physical flows are identified. This enables checking mass and energy balances, which is very important for verifying and validating the model.

### World market

The world market represents both foreign electricity producers, that can supply electricity to the Dutch market through the electricity grid of Europe, and the companies that sell fuels used for electricity production. The goal of the world market is to sell fuels and imported electricity to the Dutch electricity sector.

The market is accessible for all parties. Price and maximum capacity of import follow a trend modelled in the scenarios.

The world market can supply foreign electricity to the electricity market limited by the inter-connector capacity at a fixed price, factors that both come from the scenarios. Fuel prices (also based on the scenarios) are equal for all parties and quantities are unlimited.

### Electricity market

In this section, the electricity market agent is discussed. All trade of electricity takes place by this agent. Both the bilateral and spot markets for electricity, discussed in the second chapter, are part of this market. As was discussed earlier, perfect competition is assumed. Therefore, the integrated and decentralized market designs fit in this model. The electricity market is modelled as an agent that uses the bidding prices and amounts of all electricity producers, together with the demand of the aggregate consumer to calculate the amount each power plant will produce with the according price. The electricity market also facilitates electricity import.

First, the translation step from reality to the market model is discussed. Subsequently, the algorithm for calculating actual supply of power plants is presented. After that, the algorithm for electricity prices of power plants is discussed. The section concludes with a discussion on the import of electricity.

#### *From reality to the market model*

In reality, price forming in an integrated market takes place in periods between five minutes and one hour. Each period, a certain demand exists, assumed inelastic to price. This shifts over time (see the red line in Figure 22a). Suppliers of electricity bid full capacity at the minimum price they want to sell. After ordering this to the price bid, the blue line for this can made as well. The intersection of those two lines determines the market-clearing price  $p_{\text{hour}}$  and amount  $q_{\text{hour}}$  for that period. All parties *left* from this crossing will supply and receive electricity against the same price ( $p_{\text{hour}}$ ). The installations *right* from the crossing do not produce electricity. The orange area is the surplus: the amount of money that the suppliers of electricity receive more than their original bid.

In the market model of this thesis, it is assumed that the variable costs and the capacity of power plants are constant during each year. Consequently, supply bids are constant during each year. Each year, the blue curve in Figure 22a is thus constant. The curve can shift between years, because of changes in marginal costs. Demand varies during the day and the year, but is inelastic to price. Consequently, the (red) demand line is vertical. Changes in demand during the day and the year result in a horizontal shift of the (red) demand line in Figure 22a. As a consequence, the market-clearing price varies over time. How many hours a power plant runs per year is therefore based on the bidding price and that variation in demand. A lower bidding price means that during more hours of the year, the market clearing-price is above the bidding price and the bid is left of the intersection in Figure 22a. Aggregated to yearly basis this means that at a higher bidding price, the power plant is used less frequently. Therefore, the *average used capacity* during the year is lower. Consequently, the capacity sold is related to the bidding price in the relation drawn in Figure 22b. The bidding price is negatively correlated to the percentage of the capacity that is actually sold.

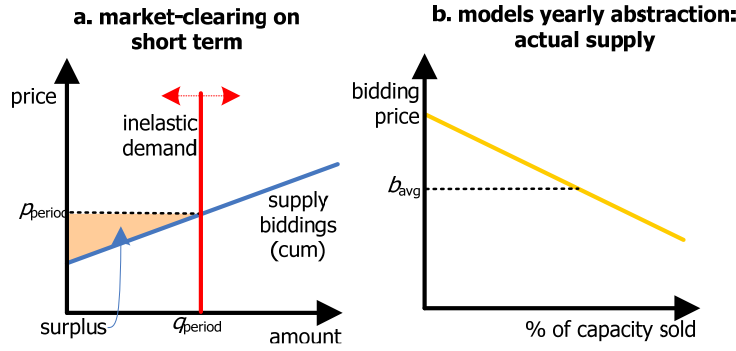


Figure 22. From short-term to a yearly market-clearing process.

In Figure 22b,  $b_{avg}$  is the average capacity weighed bid of supply. That is an indicator for the *relative height* of each bid. The average capacity weighed bid of supply is calculated with the following formula:

$$\text{average capacity weighed bid [€/MWh]} = \frac{\sum_{i=1}^n (\text{supply capacity plant}_i \text{ [MWh/year]} \times \text{bidding price plant}_i \text{ [€/MWh]})}{\sum_{i=1}^n \text{supply capacity plant}_i \text{ [MWh/year]}} \quad (13)$$

This average bid is weighed to the capacity of the bids. It should be noted that  $b_{avg}$  does *not* equal the average electricity price. It is used as indication of the height of a supply bid. That indication is used to calculate actual supply and electricity price of each power plant.

See Appendix E for the validation of the used market model. Based on historic data, running capacity of power plants under peak demand is slightly overestimated in this model. Consequently, disinvestments in the model will probably occur less often than in reality.

#### *Actual supply of power plants*

Based on the argument that the bidding price determines the amount of capacity sold, the following formula calculates how much each installation will supply in a year:

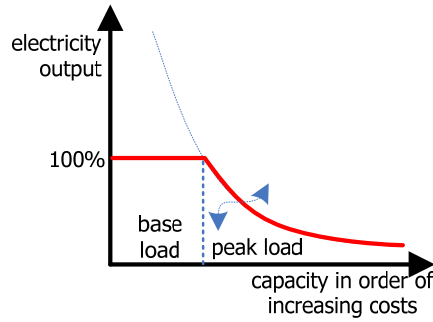
$$\text{supply of plant} = \text{supply capacity plant} \times \frac{\text{total demand}}{\text{total supply capacity}} \times \frac{\text{average capacity weighed bid}}{\text{bidding price plant}} \quad (14)$$

In this formula, the units are not displayed for reasons of readability. Recall that the unit for capacity are all in MWh/year. The outcome of this formula is drawn in Figure 23. The last term quantifies the relative height of the bid: a higher bid results in a lower actual supply. The plants are ordered in increasing costs and the most expensive plants are deployed last.

The second term in this formula indicates the amount of *reserve capacity* in the market. By including this term, total supply of all power plants will equal total demand. This term determines the slope of the graph in Figure 23. The blue double-pointed arrow indicates the influence of this term. If reserve capacity is smaller, the red line will be higher and more installations will become part of base load.

The first term means that the actual electricity supply of installation is also determined by its capacity. The actual supply of each installation is limited to 100% of its capacity. As shown in Figure 23, this limitation is imposed for all power plants that are part of base load.





**Figure 23. Electricity output of different installations based on bid price.**

#### *Electricity prices for power plants*

As mentioned above, the bids of power plants determine the frequency of their usage. In reality, the price for electricity shifts during the day and during the year because of variation in demand. Consequently, the actual price received for the electricity produced by a specific power plant of a whole year, is – as with the capacity sold – related to the height of the bid. A high bid implies peak load and operating in times of peak demand implies high prices. This is translated to a formula that calculates the price for the price for a year of selling electricity of an installation:

$$\text{price for installation [€/MWh]} = \text{average electricity price [€/MWh]} \times \frac{\text{bidding price installation [€/MWh]}}{\text{average capacity weighed bid [€/MWh]}} \quad (15)$$

The average electricity price for a whole year cannot be calculated based on bidding prices, demand is inelastic: there is no demand *curve*. Therefore, the yearly average electricity price for all installations is determined by the total supply capacity and demand in the market and a calibration factor of 40 is used to generate realistic prices. The formula for the yearly average electricity price is:

$$\text{average electricity price [€/MWh]} = 40 \text{ [€/MWh]} \times \frac{\text{total demand [MWh/year]}}{\text{total supply capacity [MWh/year]}} \quad (16)$$

See Appendix E for the validation of the used formula to calculate electricity prices on the electricity market.

#### *Import of electricity*

In addition to trade of domestic production, trade of electricity import is facilitated by the electricity market as well. The lowest price of the market bids is compared with the price for import. If the price for import is even smaller, it is assumed to be dominant. Import dominance implies that the inter-connector is always used to full capacity. In case of a non-dominant import (bidding price is equal or higher than other bids), import capacity is modelled as another aggregate electricity producer on the market. The bid will be counted as any other and the average capacity weighted supply bid will be adjusted. The contracts are finished with the calculated information and all transactions are processed as well as the physical flows of electricity.

### **CO<sub>2</sub> market**

The CO<sub>2</sub> market facilitates trade of CO<sub>2</sub> emission rights. In this model, the market follows an abstract form of the schemes used on CO<sub>2</sub> markets such as New Values (New Values 2006). On that market, a platform completely facilitates anonymous auctioning and the administrative aspects of bilateral trade. That market functions under perfect competition.

Prices on the CO<sub>2</sub> market are unknown. Only little historic data is available at this moment. Prices between January 2005 and October 2006 were between €8 and €33 per ton CO<sub>2</sub> rights (Cozijnsen 2005). The prices in the model are based on these data. Prices are relative to the amount of scarcity in the CO<sub>2</sub> market and therefore based on the supply of rights (the cap set by the government, increased with the

amount of additional JI/CDM allowances bought) and the demand for rights (the actual emission) and are calculated with the following formula:

$$\text{price CO}_2 \text{ right [€/ton]} = 10 \text{ [€/ton]} + 40 \times \left( \frac{\text{total emission [ton/year]}}{\text{total cap [ton/year]}} \right)^2 \quad (17)$$

The base price for CO<sub>2</sub> rights are 10 €/ton, around the lowest market price so far. The total cap (the domestic cap for the electricity sector and the acquired CDM and JI allowances) divided by the total emission of the electricity sector is an indicator of the scarcity in the market. This scarcity factor is squared and than 40 times added. This causes prices to be more volatile at higher scarcity. When the complete cap is used by electricity consumption, a price of 50 is the result. However, beyond the imposed cap, rights can be acquired, against even higher prices. That coincides with possibilities to exploit JI/CDM projects that result in CO<sub>2</sub> rights. The theoretical maximum amount of rights is in this model unlimited. In the calculation of the price in the model, a one percent normal distribution is added to this price to account for the unpredictability of the market.

## 4.6 Definitions of technological installations

Next to the agents, technological installations, such as power plants are used in the model. By choice of definition, technological installations are not agents, because they do not act autonomously. Technological installations make no decisions. A technological installation is modelled as a black box characterised by inputs and outputs. Agents own, operate and control technological installations. The definitions of agents, as stated above, include behaviour for that control. However, in reality control and decision making can be physically integrated in technological installations. All decision-making is assumed to take place in agents.

The main types of technological installations are power plants and installations capable of delivering fuels. Physical goods can only be transported from and to technological installations, owned by agents. As a consequence, a power plant is a black box, owned and operated by an electricity producer that uses an energy source to produce electricity and by-products in a fixed ratio.

An overview of the power plants and their characteristics is displayed in Table 11. The main six types of power plants in The Netherlands are modelled, namely a nuclear power plant, a wind farm, a combined cycle gas turbine, a biomass power plant, a coal fired steam power plant and a clean coal power plant. Heat is modelled as a by-product that emitted to the environment.

**Table 11. Overview of power plants, relevant properties, inputs and outputs.**

<i>types</i>	<i>properties</i>	<i>inputs</i>	<i>outputs</i>
nuclear power plant	lifetime	uranium	electricity
combined cycle gas turbine	construction time	natural gas	water vapour
coal fired steam power plant	construction costs	coal	heat
wind farm	maximum capacity	bio-fuel	exhaust
clean coal power plant	operational costs	air	CO <sub>2</sub>
biomass power plant	area	wind	

The basic inputs of these plants are fuel and air, or an energy source. The main output is electricity. All other flows are modelled relative to the electricity output. Other outputs are by-products or emissions, such as heat, water and CO<sub>2</sub>. The data sources and calculations used to model the input-output structures and the properties of these power plants can be found in Appendix B. Because efficiencies are assumed to be constant in time, also the input-output structure is constant. Energy and mass balances of these input-output structures are correct in the sense that all relevant goods are included. Next to electricity, heat, CO<sub>2</sub> and water vapour are the main outputs. Exhaust contains all yet unnamed outputs of a power plant resulting from impurities in the input.

Besides power plants, there are some other technological installations of relevance. Delivery installations are used to supply the fuels needed for power plants to produce electricity. The world market is owner of delivery installations for coal, gas, bio-fuel and uranium. Note that the import of electricity is modelled as a delivery installation owned by the world market as well. World market prices for fuels and electricity import are modelled as changing properties of the delivery installations. The limitation to the inter-connector capacity is modelled as maximum capacity of the electricity delivery installation. The consumer has an electricity consuming technological installation that represents all apparatus consuming the contracted electricity. The environment accepts, as discussed above, emissions and unwanted by-products. Because physical flows only can run to a technological installation, the environment also owns a technological installation that represents all 'end of pipes'.

## 4.7 Emerging system structure and behaviour

Agents, mainly electricity producers, make autonomous decisions, act and interact, based on their goals and means. They use the data in exogenous parameters, defined in the scenarios. The agents own, invest and disinvest in technological installation in order to fulfil their goals.

The result of those individual actions is a system level structure of CET and electricity sector. Figure 24 displays a structured overview of the system structure that *emerged* after a few years during a simulation run. Therefore, this is the result of the action and interaction of agents. Agents in this period invested, disinvested, traded, generated and supplied electricity. The figure is a representation of the system the agents shaped by their actions. Note that the system would not be different if it was drawn by hand, using the same format. Remarkable is that it is not an input, but an output of the model: the structure, as displayed, was not explicitly modelled. As said above, it emerged.

The structure of the figure is based on the three-layer model introduced in chapter three (recall Figure 15 on page 25). The three layers structure the interaction between agents and technological installations. The relations and connections of the agents and the installations are drawn as lines in three colours. The *lowest* layer (displayed as the green lines) is the technical layer in which technological installations interact. This interaction is physical exchange by means of flows. For instance, the delivery of coal to a power plant that uses that coal as fuel for electricity production is displayed as a green line from the coal delivery installation to the coal power plant. The electricity produced by the same power plant is delivered to the consuming installation of the electricity consumer. By-products are delivered to the installation of the environment. The *middle* layer (displayed as the red lines) contains the relations of agents. The agents trade commodities through contracts. Therefore all communication in the model between agents is through contracts. All contracts in this model last one year. For example, an electricity producer, owning a coal power plant, purchases coal through the world market. A contract for selling electricity is signed with the electricity market. The electricity market, facilitating the trade of electricity, also has a contract with the consumer of electricity. Although the emerging physical connections based on the actions of the agents are from power plant to consuming installation, the consumer and electricity producer do not have a direct contract. By separating the technical layer from the information layer, this can be visualized. The agents thus sign contracts that imply the physical exchange between technological installations. All agents that sign contracts themselves are responsible to translate that to actions at the operational level. That means that agents have to operate their technological installations such that they meet the terms in the signed contracts. The *upper*, strategic layer (displayed as the blue lines) presents ownership relations. Agents impose changes in this layer by investing in new power plants or by disbanding old ones. Changes in this layer are slow, because of the long economic lifetime of power plants. For example, an electricity producer decides to replace a coal power plant by a natural gas power plant, because the profitability of coal decreased by the introduction of CET. Change in the upper layer is a shift in the electricity generation portfolio.

The emerging structure in the model, as displayed in Figure 24 is thus composed of these three layers of connections and interaction. Change in the structure mainly occur through change in the strategic layer. After the electricity producer replaced the coal based power plant with one using natural gas, also the two lower layers change. Changes in the middle layer occur through the used contracts. Contracts with the world market for the delivery of coal are no longer needed and will not be renewed. New contracts for the delivery of natural gas are made. In the lowest layer, physical flows change. Flows of coal stop and are

replaced by flows of natural gas. Emission flows to the environment change as well. That change in emissions is than an impact of CET on electricity generation.

Besides that three-layered structure, other parameters emerge on the system level. For instance, market prices emerge for electricity and CO<sub>2</sub> rights, based on the bids of all electricity producers. Those system level parameters have an influence on the actions taken by individual agents. For instance, electricity producers both use the prices for electricity and CO<sub>2</sub> rights in investment considerations. The influences are thus reciprocal. Consequently, the system evolves over time. Because the number of electricity producers is limited and they have different management styles and market positions, the decisions made are all unique and significant.

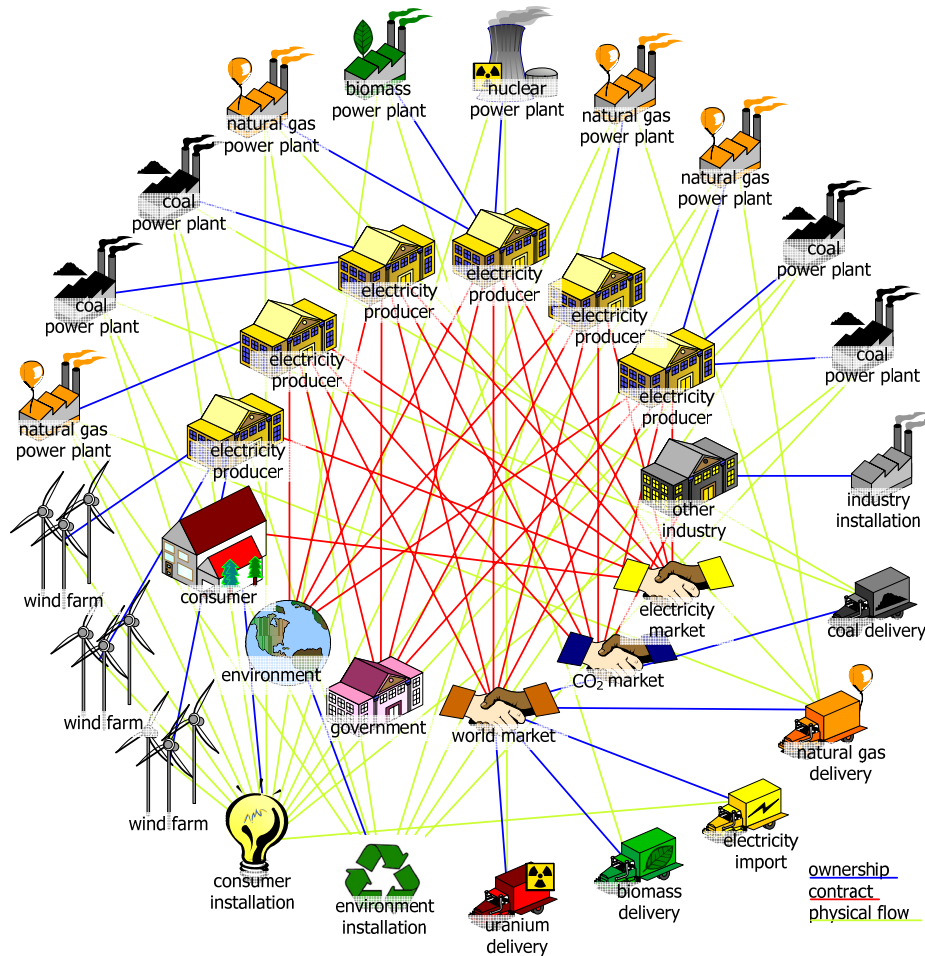


Figure 24. Dynamic network structure display with picture, following the three-layer model.

## 4.8 Conclusions

The agent-based model has a number of separate components. Assumptions were created for those components in order to build a functional and complete model. First, the sequence of potential actions of agents was identified. Agents are given the opportunity to execute operational and subsequently strategic actions. Electricity producers operate power plants, acquire fuels and CO<sub>2</sub> rights, and decide on (dis)investment in their generation capacity. The actions are executed each year. The actions are modelled in agents that decide on their execution. The agents are in control of their own actions and their owned technological installations with all their properties. The agents are influenced by many exogenous factors. Those factors are modelled as scenarios that represent different relevant futures.

The consequences of the actions of the agents are observed on the individual level as well as on system level. CO<sub>2</sub> emissions, market volumes and portfolio development are the consequence of the decisions taken by individual agents. The total system evolves during a simulation run, because the decisions by agents use the scenario data and the output of the model.

## 5 Model implementation

### 5.1 Introduction

A complete overview of the problem was given in the first two chapters. In the third chapter a selection of research tools was made. In the previous chapter, the model was presented with its assumptions, structure, agents, technological installations and emerging systems behaviour. Implementing this to a working model was a critical step in this thesis. This chapter gives insight in the implementation of all the components of the model presented in the previous chapter.

The structure of this chapter is as follows. First, a presentation is given of the agent-based modelling environment used to create the model. This environment is in progress and developments were needed to create a functional environment. The modelling environment includes a formal language for the agents. The implementation of the model structure is discussed in the third paragraph. The paragraphs after that contain remarks on the implementations of scenarios, agents and technological installations, as presented in the previous chapter. The chapter ends with conclusions.

### 5.2 The agent-based modelling environment

The agent-based modelling environment, which has been developed in the past year within the Energy and Industry Group, has grown to be able to run large agent-based models. Since this research is part of a larger research project in which agent-based simulation models are built, parts were done in collaboration. Researchers share components. The set of software tools that used in this environment are introduced in this paragraph. The complex process in which they were coupled is discussed in Appendix F. After the introduction of the software tools, details are given on the formal concept structure that is developed to be used as language for the agents.

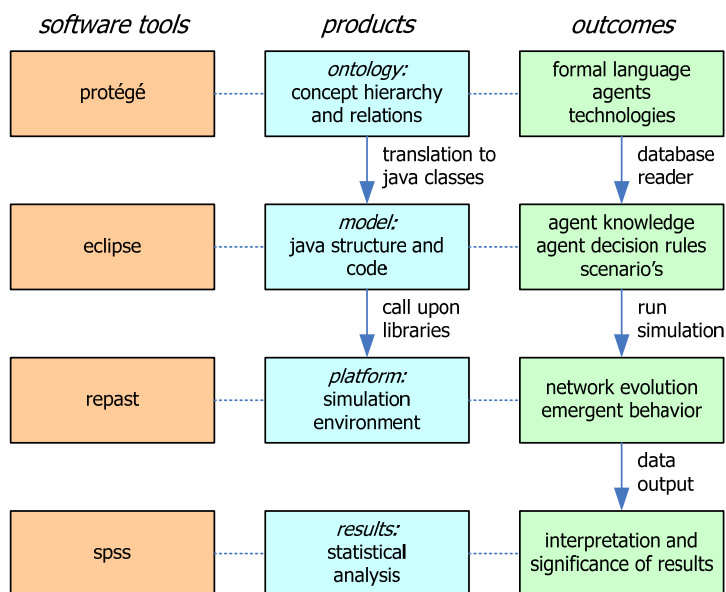


Figure 25. Software tools for agent-based modelling.

### Software tools for agent-based modelling

No complete software packages exist to implement and analyze the results of an agent-based model. A set of coupled software packages covers the support for all steps needed to come to such a simulation. Figure 25 gives an overview of the software tools used in this project. Most tools are open source, meaning they can be freely used and complemented.

The first tool used is Protégé. An ontology (a structure of concepts and their relations) is used as interaction language for agents. Because agents in these models are autonomous and undertake actions, they need a method for communication and the ontology provides the words. The ontology, created in Protégé (Protégé 2006), provides that formal language. Protégé also contains a database with the agents and technological installations used in simulations, but without their behaviour.

This structure is the input for the model, written in Java (Sun Microsystems 2006b). All java code is developed in the second package, called Eclipse (Eclipse 2006). It is an integrated development environment (IDE) for java programs. Eclipse is a user-friendly and sophisticated tool to develop and test java programs. A programmed database reader converts the agents and technological installation for use in the model. The model structure and agent behaviour is java code. The java program created calls upon libraries from the third tool, named Repast (Repast 2006a), using specific standards.

Repast, the third tool, is the simulation platform. Java based libraries of Repast provide possibilities for the user to set parameters, run and operate simulations and create output.

The output is analysed and interpreted with the fourth package, SPSS, an often-used statistical software package. SPSS helps visualising the results of the model, by analyzing and visualising data from multiple runs, gaining insight in statistical significance of the results and assessing the structural validity of the model.

Together these packages form a platform to create agent-based simulations. Analyses of the results of simulation runs show the range of emergent portfolio development that is statistically significant. This platform is under continuous development to remain flexible and adaptive to the needs of current and future models.

### Overview of the ontology

Because the development of the ontology is very important for the implementation of the model, an overview is presented of its main concepts.

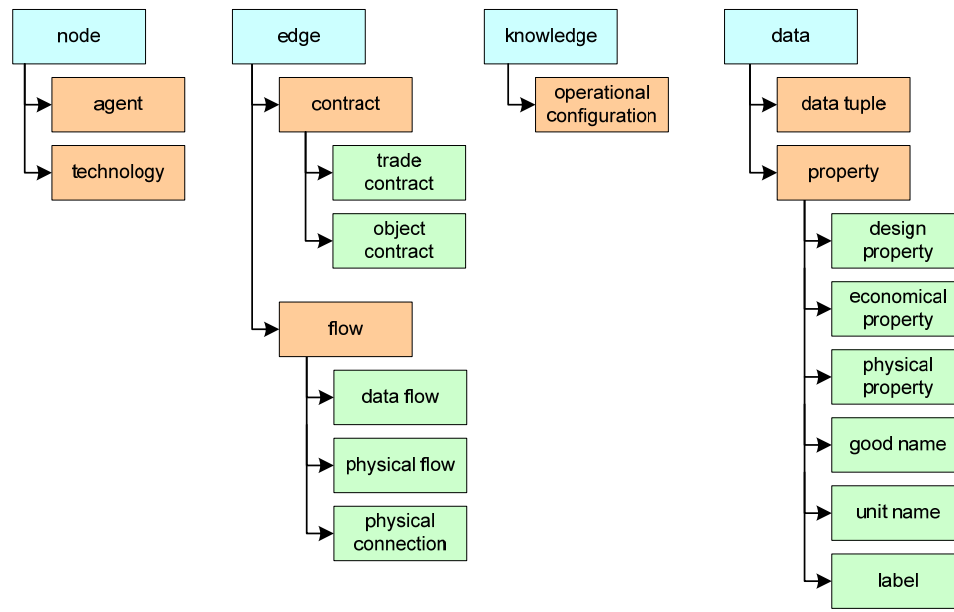
The term ‘ontology’ can be defined as follows: “An ontology is a formal explicit description of concepts in a domain of discourse (classes, sometimes called concepts), properties of each concept describing various features and attributes of the concept (slots, sometimes called roles or properties), and restrictions on slots (facets, sometimes called role restrictions)” (Noy 2006). In this paragraph, all of the concepts in this definition are discussed.

This ontology is developed in the Protégé software package, as was mentioned above. The ontology is a structure of concepts together with their relations. At the same time, it is a formal language, used as agents’ communication language. Concepts are for instance *agent*, or *contract*. All concepts are in a hierarchical structure. Properties of those concepts are for instance *price* and *label*. In the ontology, all properties are defined in concepts as well. Consequently, properties of concepts become other concepts.

Noy (2006) add to their definition of an ontology: “An ontology together with a set of individual instances of classes constitutes a knowledge base. In reality, there is a fine line where the ontology ends and the knowledge base begins.” Noy points at the difference between concepts and entities, for instance the agent *concept* and an agent *entity*. The agent concept defines what agents are and what properties they have. An agent entity is an example, an object, defined by that concept and with that properties. For instance, consider the concept agent with label as property. An agent object with as property the label “*Robert*” would be an entity. This consideration is important for understanding the object-oriented structure of agent-based models. Appendix G gives more information on the terminology and ideas of object-oriented

programming. Moreover, that appendix presents a complete overview of the concepts, together with a description of the collaboration process in which the ontology was derived.

Figure 26 presents the most important concepts of the ontology for the agent-based model of this thesis. The ontology contains four main branches of concepts: nodes, edges, knowledge and data. The hierarchical relations define locations of concepts in the tree structure. The second type of relations, as noted above, are properties of objects, defined as cross-links between objects. For clarity reasons, Figure 26 does not display the second set of relations. The remainder of this paragraph discusses the four branches.



**Figure 26. Ontology classes summary.**

#### *Node*

The main nodes are agents and technologies. In the implementation of the model, technologies are a synonym for technological installations. All nodes have economic properties, such as a price, capital and operational costs. Additionally, they have design properties, such as lifetime. Moreover, nodes have physical properties, such as location, energy and mass. Finally, nodes have a label and have edges. Edges are the links between nodes, for example a flow of stuff through a pipe. Edges are in the second branch, discussed below.

Agents are the private and public actors and the markets. They own a set of technological installations. Agents can have a form of behaviour to be able to make decisions.

Technologies, or technological installations, are black boxes with inputs en outputs. Technological installations have an operational configuration. The operational configuration, part of the knowledge branch, gives information of the input-output structure of a technological installation. It is a set of inputs and outputs with their relative amounts scaled to one specific flow, called the *reference flow*. For a power plant, the reference flow is the electricity produced. The other flows, such as the fuel consumed are relative to produce that amount of the reference flow. Technological installations also have an operational scale. The operational scale determines the actual flows per time tick. The following formula calculates actual flows:

$$\text{actual flow [\#/tick]} = \text{operational scale [\#]} \times \text{relative amount [\#/tick]} \quad (18)$$

The actual flow is the product of the operational scale and the relative amount stated in the operational configuration. The model can use any unit representing an amount, as long as units are consistent throughout the model. This way actual flows of all inflows and outflows, including the reference flow is

calculated. The operational configuration thus only describes the *relative amounts*. Only the combination with the operational scale gives insight in the absolute amounts per time tick.

### Edge

Edges are the links between several nodes. Therefore, the main properties of edges are the two nodes it connects. In addition, edges have a label and economic properties. Three types of edges are distinguished: flows, connections and contracts.

Flows can contain physical commodity or contain some data. The main characteristics of a physical flow are the *good name* – the name of the flowing commodity – and physical properties. In addition, it must have a carrier: a physical connection, such as a pipeline or a road. Technological installations can have physical connections; agents cannot. A data flow can contain information on any concept.

The main properties of a contract are the buyer and the seller. In addition, the buyer and the seller can sign the contract. A trade contract is about the trade of a flow of commodity. Therefore, it includes a reference to the traded flow. Details of the contract come with that reference. By using an *object* contract, all other objects can be traded. The model uses object contracts for trading CO<sub>2</sub> emission rights.

### Knowledge

The knowledge branch is the smallest branch at this moment. As was mentioned above, the relative input-output structures of technological installations reside in operational configurations. Agents use the operational configurations to operate technological installations. Future expansion could lead to the definition of other types of knowledge.

### Data

The data branch is a hierarchical overview of characteristics and properties of other objects. For instance, the properties of agents, technological installations and flows, noted above, are in the data branch.

The first main types of data are the properties. Three types of properties are used: economic, physical and design properties. In lower hierarchical levels actual properties, such as mass, energy, construction time and price are defined.

Commodities are named by ‘good names’. Unit names keep track the used units. Unit names are included to support dimension analysis. Labels can be helpful in representing functions that an object has: for instance, a flow is labelled to be an inflow, an outflow or an emission.

The last type of data is the *data tuple*. A tuple is defined as a smart set of properties. A data tuple is such as set, containing an amount, a unit, a good name and a set of labels. Together the data tuple gives information on the relative amount of a flow. Consider an amount 2, a unit ton, a good name CO<sub>2</sub> and a label emission. The data tuple of those properties is 2 ton CO<sub>2</sub> emission.

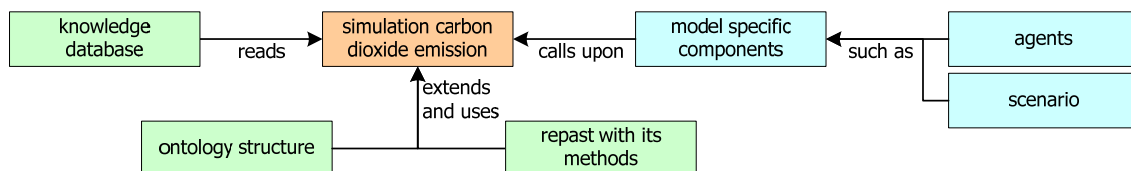


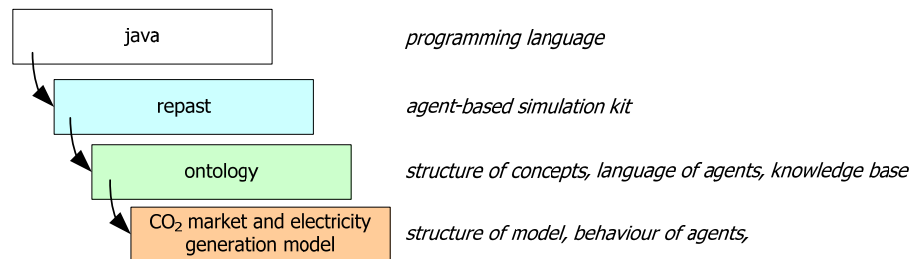
Figure 27. The role of the central model file.

## 5.3 Implementation of the model structure

The models structure with the four main actions was presented in the previous chapter. The implementation of this part encompasses more than only those actions. It is the central point in the model. The models structure is complex because all components connect, namely the concept hierarchy from the ontology, the database containing the agents and technological installations, the definitions of the behaviour of agents, the definitions scenarios and the generation of visual and data output.



Figure 27 visualizes the role of the backbone of this model. It is the model structure as well as the java program that runs the simulation. Because repast is used as underlying simulation environment, several steps had to be made that are imposed by that package. More information on these implementations can be found in the repast documentation and the tutorials (Repast 2006c; b). This file also connects with the knowledge database, uses the ontology structure and model specific components, such as the agents and the scenario. All components are separate and can therefore more easily be maintained, exchanged or replaced.



**Figure 28.** Java, repast, the ontology and the model as layers.

The content of the model structure is partly determined by Repast, partly by the ontology and partly by the model. Those four layers are displayed in Figure 28. Java is the programming language of all tools. The repast layer is necessary to be able to run a repast simulation. The third layer defines the language of the agents and all concepts used in the model. It uses concepts used by repast, as does the model itself. The fourth layer the model itself: a complex set of code that this paragraph discusses.

The main components of the model structure are discussed by a walkthrough during a simulation run with the following steps. First, the model is started, then parameters are selected for a run. Second, a simulation run starts, actions occur and display. Finally, the run stops and interpretation of the results can start.

### Starting the model

When the model starts, a set of actions prepare for simulation runs. First, repast procedures initialize the model. Subsequently, the knowledge database is read, containing all needed agents and technological installations with their properties. Agents are processed by attaching them to their behaviour. A parameter settings box is displayed after initializing the model for the end user to select the settings for the simulation run. In the box drawn in Figure 29 parameters can be set.

The parameters are on the correct value for the model runs presented in Chapter seven, except for the selection of the scenario. User can make other selections for reasons of verification, validation or for experimenting with the model. The simulation length can be set with the slide bar between 10 and 200 years. The simulation runs reported have a length of 75 years. The number of electricity producers can be set, between 1 and 6 to see what the effect of the amount of players is on the market. The initial electricity market price can be changed (in €/MWh) as well as the initial percentage reserve capacity in the electricity market. The initial aggregate demand for electricity (in TWh/year or  $10^6$  MWh/year) is optional for change as is the initial demand of the industry for CO<sub>2</sub> rights to be bought on the CO<sub>2</sub> market (in Mton/year). CET can be disabled to run simulations without CET impacts. The initial electricity generation portfolio distribution can be randomized. The non-random starting distribution is according to the Dutch 2004. Moreover, management styles and market positions for the electricity producers can be randomized. The non-random selection of management styles and market positions was presented in the previous chapter.

Textual messages, visual output and data to file output can be separately switched. The purpose of the model runs determine the usefulness for different types of output. File output is used for multiple runs that are to be interpreted, visual output for exploring single runs and textual output for verification. Limiting graphical and textual output result in faster model runs.

The screenshot shows a 'Model Parameters' window with the following settings:

- ScenarioNumber:** Scenario 0 (dropdown menu)
- SimulationLength:** 150 (slider from 0 to 200)
- NumberOfElectricityProducers:** 6 (slider from 1 to 6)
- InitialElectricityPrice:** 30 (slider from 10 to 50)
- InitialOverCapacityPercentage:** 20 (slider from 0 to 100)
- GrandfatheredPercentage:** 90 (slider from 0 to 100)
- InitialAggregateElectricityDemand:** 106 (slider from 50 to 140)
- InitialIndustrialCO2Demand:** 1 (slider from 0 to 10)
- UseCO2Trade:** ☒
- RandomInitialPortfolio:** ☐
- RandomCharacters:** ☐
- DisplayGraph:** ☒
- UsePictures:** ☒
- WriteToFile:** ☐
- DisplayTextualMessages:** ☐

Figure 29. Parameter settings.

### Implementation of the sequence of actions

The sequence of actions, as was discussed in the previous chapter contains the following potential actions of agents:

- trade electricity through the electricity market
- acquire the resources needed for the contracted supply of electricity
- acquire CO<sub>2</sub> rights
- make investment and disinvestment decisions

A schedule contains these actions, as well as code for updating statistics and the selected output. This schedule is a mandatory element for agent-based simulation with repast. The implementation is such that each tick in this model represents one year. During each tick, the same sequence of possible actions is used.

### Implementation of visual and data output

The development of output is a key element for analysing results and communication with users. Several types of graphical output are modelled. First, the structure of the agents and technological installations can be visualized. Second, the levels of parameters over time can be displayed. Third, textual output to a console can be used. Finally, data output to a file is developed.

*Network structure graphics* are useful in displaying how interactions of agents and technological installations evolve. An example of the network structure display is on the cover of this document. A display of the network structure updates each on tick and shows important qualitative information on emergent properties of the system as well as the system structure. It shows the agents, the technological installations and their relations and connections. The three-layer model was used to develop this display. The display distinguishes two circles: the agents are in the inner circle and the technological installations are in the outer circle. Additionally, more information on agents and the technological installations can be acquired by clicking on them in the display. It opens a box with the properties of the clicked item.

*Parameter graphs* display the change in parameter values during a simulation run. Those graphs can be useful to grasp evolving system or agent properties. Developments have been made to couple the statistics used to in parameter graphs to data output. Table 12 gives an overview of parameters of the graphs in the model.

*Textual output* gives very detailed and specific textual information to the user during simulation runs of the actions of agents. Textual output is used for validation and verification during the development of the model.

*File output* is used to record statistics of multiple runs for analysis with the statistical package SPSS. The statistics used are the same as the parameter graphs (see Table 12).

**Table 12. Parameters used in graphs and file output of the model.**

<i>parameters related to electricity production</i>	<i>parameters related to CET</i>	<i>parameters related to agents</i>
overview of the generation portfolio	CO <sub>2</sub> emissions	capital of all agents
yearly average electricity price	CO <sub>2</sub> cap	generation portfolio per electricity producer
total supply and demand for electricity	grandfathered rights	investment costs, CO <sub>2</sub> costs, fuel costs and
electricity import price and capacity	CO <sub>2</sub> market volume in € and ton	other operational costs per electricity producer
prices for coal, gas, uranium and bio-fuel per GJ		

## 5.4 Implementation of the scenarios

The scenarios are a completely separated section of the model. Note that this is the only place where data is entered in the model, next to the knowledge database (discussed below). Quantified data and trends are modelled per scenario axis, which makes editing the scenarios user-friendly. Initial scenario values and trends are applied based on the scenario selection at the beginning of a simulation run. Appendix C discusses the actual values and trends.

In addition, other data is processed in this component as well. For instance, the component takes care of processing the selection for random or specific management styles and market positions for electricity producers. Another example is the selection for a random or specific start-up portfolio distribution. Finally, the ranges of possible sizes for the power plant types are modelled in this component. It must be noted that all other properties of power plants come from the knowledge database. This is not possible for power plant sizes, because they are all different, within that range.

## 5.5 Implementation of the agents

The agents (and technological installations) come from the knowledge database. The knowledge base is accessed with Protégé, where also the ontology was built. This is a user-friendly way of creating the agents. Buttons and fill-in forms help in developing the properties of agents. Programming efforts are unnecessary. The agents described in the previous chapter are in the database. It is important to realize that agents in the database do not have behaviour but are only a bunch of related objects.

All agents in the model are agents of a lower level than the concept agent that is in ontology. Moreover, it is also a lower level *node* than the nodes of repast. The agents in the model are more specific agents, called *CO<sub>2</sub> agents*. The different types of actors in this model are represented by different types of lower level CO<sub>2</sub> agents to be able to add agent-specific behaviour. For instance, an electricity producer is not a CO<sub>2</sub> market, but they are both CO<sub>2</sub> agents. See Figure 30 for a visualisation of the described levels.

The behaviour of the agents is implemented in java methods, according to the definitions in the previous chapter. The sequence of actions calls upon these java methods. The methods themselves code decisions, actions and interactions. Therefore, which specific actions there are, and whether any action is taken, is autonomously decided by the agents through their methods.

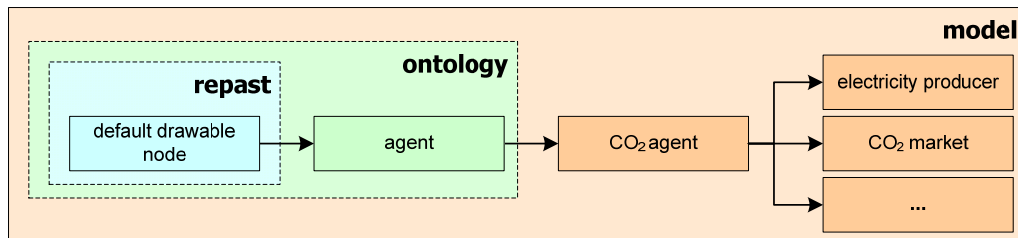


Figure 30. Repast, ontology and model layers of the agents.

## 5.6 Implementation of the technological installations

As explained earlier, technological installations are assumed not to have autonomous behaviour. Definitions of technological installations contain a name, a variety of properties and the input-output structure. Because of the absence of behaviour, the technological installations are implemented in the knowledge database. Therefore, modelling power plants and other technological installations is user-friendly. Figure 31 displays an example of the development of the input-output structure of a natural gas power plant. Note that data of power plants are in the knowledge database. As was mentioned earlier, the knowledge base together with the scenario component contains all data of the model.

Label

FromNaturalGasByCombustionInCCGT

Observer

OperationalInputs

goodName	relativeAmount	unit	functionLabel
naturalGas	222.0	m3	Primary
air	2116.0	m3	Ubiquities

OperationalOutputs

goodName	relativeAmount	unit	functionLabel
waterVapour	444.0	m3	AcceptedByPro...
electricity	1.0	MWh	ReferenceProd...
CO2	0.437	ton	LimitedEmission
heat	1.22	MWh	WantedByProd...
exhaust	1700.0	m3	AcceptedByPro...

Figure 31. Editing instances in Protégé.

## 5.7 Conclusions

A set of software tools are coupled to create an agent-based simulation environment, used by multiple agent-based modellers in the Energy and Industry Group. A broad structure of concepts, or ontology defines the agents and technological installations. Moreover, agents in the models communicate with those concepts as language.

The ontology contains four branches of concepts. Nodes are points in a network, such as agents and technological installations. Edges are connections between nodes, such as contracts and flows of goods. Knowledge contains the operational configurations of technological installations. The data branch contains the properties of nodes and edges.

The model is programmed as java code. The main java program defines the structure of the model, the selection of specific scenarios and agents and the sequence of possible types of actions in a simulation run. The scenario contains values for the data used in to model scenario trends but also other data that is used in the model. The knowledge database defines the implementation of agents and technological installations. Agents have behaviour that is modelled in java code. In that code, the agents autonomously decide whether to undertake specific actions.

The result of this implementation is a transparent model in which all components separately can be maintained, exchanged and further developed.

## 6 Model limitations and validity

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### 6.1 Introduction

The problem has been analyzed in the first chapters and using the paradigm selected in chapter three, a model and its implementation were presented in the fourth and fifth chapter. This chapter elaborates on the verification and validation of the model. In addition, the models' limits and possibilities for extension are discussed. In the next chapters, the valid model will be used to generate results and come to conclusions. The key criterion for validation is that the model should be capable to fulfil its intended use.

Because of the assumptions made and the approach chosen, the model has specific limitations for its use. The limitations are discussed in the second paragraph. Subsequently, the possibilities and recommendations for extension are given in paragraph three. After that, details are given in paragraph four on the selection of validation tests. Two types of tests are used: paragraph five reports on direct structure tests; paragraph six gives the results of structure-oriented behaviour tests. This chapter ends with conclusions on the validity of the model.

### 6.2 Limitations to the use of the model

The intended use of the model is to identify and give insight in the impacts that CET may or may not have on long-term development of the Dutch electricity generation portfolio. The basic underlying thought is that individual decisions of electricity producers are relevant to those impacts, because in a liberalised electricity sector, investments are made at the level of individual electricity producers. The agent-based approach respects this fact. However, the behaviour of real actors is complex and unpredictable. Modelling that behaviour can only be done by making assumptions and simplifications. The main assumptions were discussed in paragraph two of chapter four. Here the consequences of those choices are presented.

The main limitation to the use of the model is that it does not predict the future of CO<sub>2</sub> market prices or the exact portfolio distribution. However, that is not the intention of the model. Such a model should incorporate many aspects that are beyond the scope of this project, for instance detailed, country-specific environmental regulation, details on depletion of resources and the modelling of the market players in electricity generation of the EU. The models intention *is* to quantify the ranges that can be expected of the *effect* of CET on distribution of the Dutch electricity generation portfolio. The effect of CET is quantified by the comparison of simulation runs with CET installed to simulation runs in which CET is absent but everything else is equal. By means of scenarios, the effect can be tested under different settings.

As was argued in chapter four, the Dutch electricity sector is physically shielded from the rest of Europe, because of limited inter-connector capacity and significant losses over long distances. It is not expected that the inter-connector capacity will grow significantly more than demand and therefore the physical supply of electricity will remain a regional product. That means that the model is useful for the Dutch electricity portfolio, which was selected to illustrate this model with. However, the actors in the European market are not bound to physical limitations. Foreign market players can merge or take up Dutch electricity producers. Consequently, the market players of the EU are relevant for the number of players in Dutch electricity generation. In the model, the number of electricity producers is static. That gives the possibility to observe the long-term consequences of *specific* behaviour on the electricity market, grasped in the management styles and market positions of electricity producers. In addition, simulation runs with

other numbers of players can be used to explore the effect of the number of players. The model can at this stage not be used to simulate the impact of new entrants and merging market players.

The model simulates developments in the Netherlands, but only few country specific modelling choices were made. Therefore, the same model can be used to simulate other countries of which the inter-connector capacity is limited. All country specific data is modelled in the scenarios and can be replaced by values for other countries.

Prices for CO<sub>2</sub> rights are the main driver for emission reductions by CET. The model is not developed to predict CO<sub>2</sub> market prices. The used price model is based on available the historic data. However, the data is limited and future empirical data should be used to improve that model. The outcomes are only valid under the price levels for CO<sub>2</sub> rights of the model.

The model only gives insight in the impact of CET. Other policy is not incorporated, but can have influence on the development of the electricity generation portfolio as well. Furthermore, regulation is static. That is valid under the assumption that the government does not interfere in the system. If the system would become unstable and substantial problems would occur, governments would probably intervene to increase affordability and reliability of electricity supply.

The model does not cope with unavailability of fuels or emission rights. Scarcity leads to higher prices, but supply is always possible. For emission rights, this implies that there always are enough possible projects to receive JI or CDM rights or that parties in other countries are willing to sell them. For fuels, this means that resources are unlimited within the simulation period. The proven reserves at this moment can account for that (see paragraph 2.5). Only for the natural gas reserves are smaller, but under higher prices more natural gas is sold on the Dutch market. In addition, more conversion possibilities from other fuels are profitable at that price levels.

The simplified investment decision has consequences for the output. Trends are not observed and taken into account. This means that consequences of players' actions might be more volatile than in reality, for instance investment cycles are more extreme than they would occur in reality. However, the impact of emission trade can be observed by comparing the same system modelled with and without emission trade. The model gives mainly insight in relative outcomes.

The model does not account for differences in financial power for the electricity producers. Furthermore, the model shows the impact of CET for the current set of power plant types, because technological developments are absent. The delay in emission reductions, because of the long time-scale of investments, may be shorter than in the model, because some power plants have (limited) possibilities to operational shifts towards lower CO<sub>2</sub> intensity. Additionally, small units can be built on a shorter time-scale than in the model. The effect of CET can therefore be larger than found in the model.

Finally, the intention of the model is not to look at the adequacy of capacity for electricity generation. The model assumes that the market strives to an adequate amount of supply capacity and the electricity producers' investments account for that. The *main* use of the model is, as mentioned, to acquire insight in the effects of CET on the development of the electricity generation portfolio. Nevertheless, insight in the impact of CET on the adequacy of generation capacity can be obtained by comparing the development of supply in simulation runs with CET to runs where CET is absent.

### 6.3 Possibilities to extend of the model

The model is setup such, that all components can be extended. In the introduction of chapter 4, in Figure 19, the components were already introduced for which extension is possible. In this paragraph, these are discussed in more detail. This discussion is summarized in Table 13. Extensions for four components are addressed separately, namely the model structure, the definitions of the external world, the definitions of agents and the definitions of technological installations. Extending the definitions and agents is most important. The importance of individual extensions is denoted in Table 13 by plus and minus signs, for important and less important respectively.

**Table 13. Possibilities to extend the model.**

<i>component</i>	<i>extension</i>	<i>importance</i>
model structure	country-specific regulation	-
	other countries	+
	multiple countries	-
definitions of the external world	governmental intervention	-
	accidents	-
	unavailability of resources	-
definitions of agents	electricity producer investment decisions	++
	(e.g. discounted cash flow, decision-making under uncertainty, risk, financial position, costs for capital)	
	disinvestment decisions	+
	entry and exit	++
	electricity market electricity trade	+
	world market by-products trade	+
	electricity consumer elasticity of demand	+
	industry other involved industrial sectors	++
	definitions of technological set of generation technologies	++
	installations scales of generation technologies	+
	learning effects	++

The main extensions to the *structure of the model* are to its scale. Currently, the model illustrates the Dutch situation. However, only few country specific parameters and regulation are modelled. Therefore, the model can be extended to incorporate more country-specific regulation. In addition, other countries can be simulated as well, in order to compare the outcome of the model for different countries. In a later stage, the model could encompass multiple sub models for neighbouring countries, or even the whole EU, in order to make claims on a larger scale. The main recommended extension in the model structure is to include parameter settings and regulations for other countries, since this can be incorporated relatively easy. However, the value of that study is determined by the amount of country-specific parameters and regulation.

*The definitions of the external world* can be extended as well. In this model, scenarios are used to model the external world. At this moment, scenarios incorporate parameter values and trends. That technique can be extended to model ‘step changes’. Step changes could be caused by governmental intervention: different regulatory changes can modelled to occur, such as subsidy regulation, or permission for electricity producers to be sold to foreign parties. In addition, accidents can be modelled as step changes. For instance, the impact of a nuclear accident on nuclear fear could be modelled. Although these extensions are possible, the scenario trends will probably remain most important in the definitions of the external world. These extensions however give more possibilities for end users of the model to play. A third extension to the external world is the incorporate the fact that natural resources are essentially limited. Based on the setup of the model, that would require a structural change. The benefit of that extension is therefore relatively low.

*The definitions of agents* should be extended in several ways. For the future of electricity producing agents, it is recommended that investment decisions incorporate extrapolated observed trends. In addition, methods such as discounted cash flow and decision-making under uncertainty are recommended to be implemented to improve the decisions made. These extensions can be also used to compare different decision-making techniques applied to this case. Furthermore, differences in financial position and power of electricity producers can be incorporated. In addition to the current model, the amount of risk an agent is willing to take can be used to invest in specific *amounts* of capacity. Disinvestment decisions can be extended as well by incorporating more advanced calculations of the economic lifetime of power plants. A first step would be to incorporate costs for capital. One of the main recommendations is to develop electricity producing agents that include behaviour to enter or exit the market. In addition, merging producers should be incorporated. If investment decisions adequately include the amount of capacity and agents can enter and exit, issues relating the adequacy of electricity generation capacity can be thoroughly addressed

Electricity trade through dedicated markets can be extended by the use of existing models and more historic data. In addition, trade of by-products of electricity generation could be modelled in order to quantify the differences between regular power plants to combined heat and power plants and trigeneration. It is recommended to include elasticity of electricity demand with respect to price, in order to simulate the long-term impact of CET on the demand for electricity.

Next to electricity generation, the sectors obliged to participate in CET should be incorporated separately. In addition, the ongoing negotiation process for the allocation of grandfathered rights between sectors and the government could be explicitly implemented. Claims on the effectiveness of CET in the Netherlands as a whole can be made after this is incorporated. Therefore, this is one of the most important recommendations.

*The definitions of technological installations* can be extended more easily than the other components. As a consequence, much benefit can be gained by investing in the development of those definitions. Additional technological installations would enlarge the set of generation technologies. Imaginary technologies can be added to simulate yet non-existing technologies. In addition, the variation within the current set can be increased by incorporating different types of power plants per energy source. In combination with trade of by-products, mentioned above, regular power plants can be distinguished from combined heat and power and even trigeneration. Furthermore, during simulation, learning effects can be incorporated to model technological innovation. For instance, the efficiency of technologies can be altered over time. Electricity producers could modify existing power plants or the power plants that can be invested in change. In addition, technological knowledge can also be modelled to differ between the agents.

In conclusion, the most important extensions to the model, marked with two plus signs in Table 13, are that investment decisions should be enhanced, entry and exit of players on the electricity market should be incorporated, all involved industrial sectors should be distinct and technological innovation of power plants should be modelled.

## 6.4 Selection of validation tests

The term validation refers to the whole testing process to make sure the model fulfils its purpose. A part of this is verification: checking on consistency, whether concepts and relations are coded correctly. Different types of models traditionally use different validation techniques. Validation methods for agent-based models are still in development. Consequently, no generally accepted validation methods are in the literature. Qudrat-Ullah (2005, page 2) argues that for validation of agent-based models many of the same tests developed for System Dynamics models can be used. He states that both model nonlinear complex systems, assume that microstructures of a system are responsible for its behaviour and aim at discovering leverage points in complex systems. Qudrat-Ullah (2005) strongly suggests using structural validity procedures and states a selection of tests to be used for agent-based models as well as System Dynamics models. A broader range of validating methods for System Dynamic Models is used. The overview of Daalen and Thissen (2001) was based on Barlas (1996). The methods applicable to agent-based models are used.

Before the tests are presented, a note is made on the role of validation during the model development process. An advantage of the model development process of this thesis and the agent-based environment is simulations can be run with preliminary models. From the start of the modelling process, preliminary results were visible. As a consequence, it was possible to validate the model during the complete development process and learn from the preliminary results. Validation techniques, as discussed below, are however not facilitated or supported by software packages. One verification tool is available, namely the JUnit test bed. However, that is developed to verify java code in general, and does not support the needed testing types, as described in this chapter. Therefore, significant modelling effort was invested in validation possibilities. Developments are recommended for validation techniques that help the modeller in validating agent-based models in a less laborious way.

Daalen and Thissen (2001) distinguish two types of validation techniques: direct structure tests and structure-oriented behaviour tests. Direct structure tests validate the model by observing the code.



Structure-oriented behaviour tests validate the model by running and interpreting the results. In the next two paragraphs, the two types of tests are presented.

## 6.5 Direct structure tests

Direct structure tests are techniques that validate by observing code. The model does not run during these tests.

### Empirical structure and parameter check

This tests state that the structure as well as the parameters should be consistent with relevant knowledge on the system and with the real world. Most of the parameters, such as prices are real world parameters for which data sources are used. Data sources used as input to the model only include reliable statistics sources, such as national governmental agencies and branch organizations. If data sources suffice, the use of those parameters is valid. The other parameters, such as management style and market position parameters, are subjective. The use of agent-based modelling to these types of questions is new, so there is little data known on that subject. Variation in these values is used, in order to quantify differences between electricity producers. It is argued that the parameters selected should all be included in the model and expert input was used to validate this selection. The same holds for the model structure. The structure of the model, contained by the potential actions of agents, corresponds with reality on a yearly time scale.

### Direct extreme conditions

In System Dynamics, all model equations are tested to extremes, because the consequences of extreme parameter settings are easy to estimate. Most of the agent-based model however does not use direct mathematical formulas. The result of extreme parameters can only be checked by running the model. Therefore, the larger part of extreme conditions tests are presented in the section on extreme conditions tests found in the next paragraph. Some formulas were used, for instance to model the electricity market. See Appendix E for the validation of electricity market model. In addition to the tests presented in that appendix, all formulas used were tested to extreme conditions and the expected result to those conditions was found.

### Boundary adequacy of structure

The delineation of the system is very important. Because of the complexity of the subject, a system with relevant technical, economic and social aspects, on a crossing of disciplines and sectors, it is difficult to come to a model within the scope of this thesis. A very generic model does not give insight additional to qualitative literature available. With the focus used, the relevant aspects are grasped and significant new insights can be obtained.

Top-down and bottom-up aspects are used to grasp all relevant aspects. For instance, the parameters in the scenarios are top-down. They are exogenous trends. In fact, they are simple system dynamics models. Bottom-up aspects are for instance the individual power plants and electricity producers. The electricity producers are autonomous and unique. However, some other players are aggregated for two reasons. The first reason is that individual behaviour is unknown, while behaviour of groups is easier to model. The second reason is the development of the model and/or the simulation speed can be more rapid by using aggregates. The focus of the model is not on the aggregated players; therefore, the outcomes are insensitive to modelling individuals or groups. As a consequence, all relevant system parts can be included, within the scope of one thesis project.

In addition, not all influences are modelled. The modelled selection is based on the intended use of the model. That was discussed thoroughly in the second paragraph and the previous chapter. Based on those discussions, it is argued that the intended use can be met. The structure of this modelling states very clearly what influences are assumed not to exist and this can be changed in future models.

### Dimension analysis

The dimensions (or units) of all parameters should be correctly used throughout the model. The set of concepts used in this model gives the possibility to use units in the communication, for instance in

contracts. To prevent errors and confusion, a specific set of units is used of which the main are € for money, ton for mass and MWh for energy, m<sup>3</sup> for volume and year for time. The unit for the capacity of power plants is thus MWh/year, instead the more conventional MW. Input data is in those units to be able to be consistent throughout the model. Consistency in the use of units is continuously checked during development of the model; units are assumed to be applied free of error.

### Face validation

Face validation is the use of expert opinions to validate the structure of the model. Face validation is difficult for this the modelling of this system, because the system is so innovative and multidisciplinary, the experts cannot fully face validate such a model. However, building the model has been done after, and during the consult of various experts in the energy and industry domain that are part of the Energy and Industry Group.

## 6.6 Structure-oriented behaviour tests

Structure-oriented behaviour tests are techniques that validate the model by observing the output of a running simulation. The implemented outputs types (see the previous chapter) are used for validation. Especially textual output shows the working of specific parts of the model in detail. The order in which specific parts of code are processed is tracked, as well as the values that parameters have at certain moments in time. This helps in finding conceptual and coding errors. In addition, with graphical output, the correct functionality is verified. Textual and graphical outputs are used in the structure-oriented behaviour tests.

### Extreme conditions

To test whether the behaviour of the model is correct, extreme parameter settings are used. As was stated in the last paragraph, most extreme conditions tests are done by running the model. Verifying the models output is more straightforward under extreme conditions than under normal conditions. Therefore, these tests give insight in the correctness of (inter)dependencies in the model. An example of this test is running the model under the condition of zero demand for electricity. Under this extreme parameter, not new power plants are built, no CO<sub>2</sub> rights are bought, no contracts are made and no physical flows are created. In fact, a static system is the result. This result is intuitively correct. Extreme conditions tests are often used during the development of the model to check incremental developments of the model. Many extreme conditions are tested. Therefore, the validity of the model is increased.

### Qualitative features analysis

In contrast to extremes, the model behaviour is also tested with specific parameter settings. Qualitative properties of the model are validated by running these types of experiments. For instance, by increasing the industrial demand for CO<sub>2</sub> rights (a scenario parameter), the market price of CO<sub>2</sub> rights should increase as well as the market volume. As with extreme conditions tests, the order in which actions occur are tracked, as well as the values of parameters at specific moments during simulation runs. Another example of a qualitative features analysis, is a test in which the yearly costs per electricity producer is displayed, distinguished per type of costs. One can observe that investment costs are made in peaks. In contrast, fuel costs occur each year. In addition, by including the information in the network structure display, validation possibilities can increase. For instance, if an electricity producer only owns wind farms, he will not have any CO<sub>2</sub> emission and therefore have no CO<sub>2</sub> costs. As indicated, by combining information of all types of output, insight is obtained in the models functioning and its validity. Many these tests are performed, mostly during model development. Consequently, the validity of the model is increased.

### Comparison with accepted theory

It is useful to compare the results of the model with accepted theory. Little theory on CET impacts is widely accepted at this moment. In addition, a body of literature on validation of agent-based models is still lacking. No quantitative literature is available with the focus of this thesis other than what is used to build the model. There are no studies to compare with the simulation outputs of the model. However, comparison is possible for parts of the model. For example, from preliminary versions of the model,

*investment cycles* were observed as negative social side effect of liberalized electricity generation (see chapter two for more details on investment cycles). That observation was remarkable, because it was *not* directly implemented in the model: it was an emerging property of the dynamics of the simulation. Investment cycles are the emerging result of investment decisions, made by individual, autonomous electricity producers that have imperfect information. In this agent-based model, the occurrence of investment cycles is different from the models used in the traditional literature. In traditional literature, investment cycles are qualitatively derived or explicitly modelled to show that they can possibly exist. Other comparison with accepted theory is only limitedly possible.

### **Sensitivity analysis**

Sensitivity analyses identify parameters to which a model is sensitive. All input parameters are varied within 10% of the 'correct' value, with all other parameters held constant. The zero scenario is used in this analysis. The variation of the output is measured under the 10% change in input. A change in the output of more than 10% means that the model is sensitive to the changed input parameter. Otherwise, the model is insensitive to that parameter. The change in the output is defined by two parameters. In this analysis, the average CO<sub>2</sub> market volume and the average electricity price are chosen. Those are main indicators of CET and electricity generation respectively. Because the model uses many stochastic elements, the analysis also needs to address the statistical significance of the changes in the output.

Several types of input parameters are used in the analysis. First, the scenario input data is analysed. Second, the sensitivity to the scenario trends is analysed. The management style and market position parameters used to describe the electricity producers are used as input as well as all properties of power plant types. See Appendix H for the procedure, the complete list of parameters and all outcomes.

The first and main conclusion of this analysis is that the model is not sensitive to variations in input. Most parameters individually do not have a large influence because the model has many input parameters that are relevant. The discussion below presents outcomes per type of parameter.

#### *Scenario input parameters*

Two fuel prices seem to be sensitive for the average electricity price. It is acceptable that the model is sensitive to fuel prices, because they largely determine the profitability of specific power plant types. The sensitivity to specific fuel prices in the analysis is caused by the dominance of those fuels in the electricity generation portfolio during the scenario that was analyzed. The model is sensitive to the demand for CO<sub>2</sub> right of the industry, because the demand of the industry is relatively large compared to the demand of the electricity sector in the used scenario. The part of the rights grandfathered has a large influence on the average market volume, mainly under low market volumes.

#### *Scenario trends*

The output of the model is sensitive to the scenario trends. The results of trends grow over time and the relatively long time scale is therefore the cause for that sensitivity. Sensitivity of the average electricity price to the demand for electricity, trends in fuel prices and electricity import prices is straightforward and acceptable.

#### *Management style and market position parameters*

The model is insensitive to the management style and market position parameters of electricity producers. This is a positive result, because of the subjectivity of the management style and market position parameters. Their impact of the exact values on the outcomes of the model is small. This confirms the validity of the model, because the consequence of subjectivity of choices is small. Only the environmentally friendliness factor has significant influence on the electricity price, because more (costly) environmentally friendly power plants are used.

#### *Power plant properties*

A number of power plant properties have small but significant influence on the average electricity price. The effect of changes in the properties of power plant types on the outcome of the model is accepted to be related to what degree the portfolio contains power plants of that type. In other words, the effect of

changes in properties of dominant power plant types is relatively large. Because the set of properties to which the model is sensitive, are properties of dominant power plants, sensitivity to that set of influences is acceptable.

## 6.7 Conclusions

Most important extensions to the model that are recommended to develop are enhancing investment decisions, incorporating entry and exit of players on the electricity market, distinguishing all involved industrial sectors and modelling technological innovation of power plants.

The main criterion for validity is whether the model can fulfil its intended purpose. The intended use of the model is to identify and give insight in the impacts that CET may or may not have on long-term development of the electricity generation portfolio. The complexity of the system is grasped by using top-down aspects for scenarios and bottom-up aspects for individual behaviour of electricity producers. This coincides with the fact that many aspects are related to the investments made at the level of individual electricity producers.

Validation tests were mainly incorporated in the model development process. As a consequence, many tests were performed on preliminary models as well as on the final model. Interaction with experts helped in that process. These tests have resulted in the correction of coding and conceptual errors. Extensive sensitivity analyses gave insight in the fact that for most individual parameters, the influence on the model output is modest and similar to reality. The performed tests confirm the validity of the model.

The impact of CET is observed by comparing developments of the electricity generation portfolio and CO<sub>2</sub> emissions of simulation runs with CET to simulation runs in which CET is absent.

## **Part III. Results and reflection**



## 7 Simulation results

### 7.1 Introduction

Part I of this thesis presented an exploration of the problem and the approach. In the previous part, Part II, an agent-based model was presented with the aim to elucidate the impacts of CO<sub>2</sub> emission trade (CET) on developments of the electricity generation portfolio. In this chapter, simulation runs of that model are presented. The model uses a number of inputs in its simulation runs in order to generate the outcomes of this model (see Figure 32). This chapter presents those outcomes.

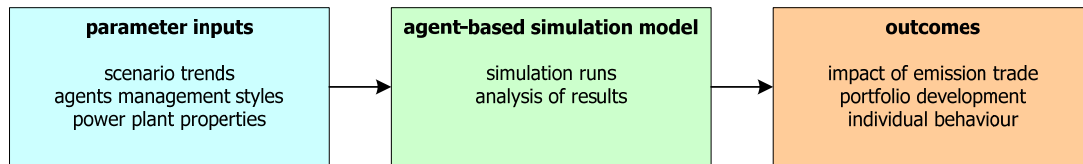


Figure 32. Inputs and outcomes of the agent-based model.

The simulation length of the reported runs is 75 years and all nine scenarios developed in chapter four are run 50 times with and without CET, providing possibilities to statistically indicate uncertainty in the results.

In chapter 2, the following three criteria were derived that assess the impact of CET on the electricity generation. The first criterion is that a reduction of emissions by electricity generation should be achieved relative to a situation without CET. The second criterion is that the cap on the emissions for the electricity sector, as set by the government, should be maintained. The third criterion is that no indications may be found of costs unnecessary for the reduction of emissions.

In the second paragraph, the input parameters of the simulations are presented. In the third paragraph, the uncertainties in the outcomes are sketched. This is done by looking at the types of uncertainty that are observed. In paragraph four, outcomes on the impacts of CET on electricity generation are presented. Findings on the emission market itself are presented in paragraph five. In paragraph six, results on the individual level of electricity producers are presented. The final paragraph presents the conclusions of this chapter.

### 7.2 Parameter space

Simulation runs of the agent-based model provide results based on specific inputs. The inputs of the model are a set of parameters, in other words, the 'parameter space'. Three types of parameters are used, that are displayed in the left, blue box in Figure 32.

For this model, scenarios were developed that represent all relevant exogenous factors. The scenarios define a number of patterns for the factors, which represent possible futures. A discussion of the values and trends is presented in Appendix C. The scenario parameters include the demand for electricity, the average margin in the supply bids of electricity producers, the external demand for emission rights on the CO<sub>2</sub> market, fuel prices, governments expenditures on JI/CDM rights, technology specific subsidies, the cap width, the number of rights grandfathered by the government, electricity import price and capacity

and the types of technology that are available. All nine scenarios use different combinations of trends that these factors follow over time.

The second set of parameters contains the management styles and market positions of electricity producers. Those management styles and market positions are sets of parameters, with unique values for each electricity producer. The first parameter is the margin on supply bids of electricity producers. The second parameter is a maximum of concurrent investments that are made. Third, the barrier for each producer that is used for investing in new capacity is based on the ratio of the total supply and demand. The final four factors are used in investment decisions to weigh the criteria used to choose the preferred power plant type. Those criteria are economic profitability, environmentally friendliness, conservativeness and unattractiveness of nuclear power plants.

The third set of parameters contains technical characteristics of power plants. The input-output structure of the different power plants is used as well as power plant properties, namely the lifetime, construction time, construction costs, maximum capacity, operational costs and the consumed area.

### 7.3 Uncertainty in outcomes

In this paragraph, the uncertainty in outcomes of simulation runs are analyzed. In general, the uncertainty in outcomes increases over time, because uncertainty is the consequence of stochastic variation, that adds up over time. Uncertainty is an important concept, because it is an indication for the reliability of the outcomes and conclusions.

In (most of) the graphs in this chapter, the 95% confidence intervals are drawn to reflect the outcomes. See for instance Figure 33. Values of specific parameters are drawn over time. The circles display the average value found of a parameter on a specific moment in time. This value is the average value of all simulation runs done. The vertical lines are the 95% confidence interval. This means that with 95% certainty, the value will be within the range indicated with the vertical line, called the error bar or confidence interval bar. The length of this line represents the uncertainty in the parameter at that moment in time. No line at all, means that the uncertainty is smaller than the height of the circle.

Uncertainty in the outcomes can be measured in two ways: over all simulation runs *and* measured per scenario. Three types of uncertainty are distinguished: no uncertainty, increasing uncertainty or complex patterns of uncertainty. Table 14 gives examples of those types of uncertainties.

**Table 14. Examples of the types of uncertainty in the outcomes.**

	<i>no uncertainty</i>	<i>increasing uncertainty</i>	<i>complex uncertainty</i>
uncertainty over all simulation runs	constant parameter: capital of the environment	scenario trend: fuel prices	emerging property: portfolio composition
uncertainty per scenario	constant scenario parameter: emission right demand of industry		

#### Uncertainty over all simulation runs

In this section, the uncertainty types are discussed, measured over all simulation runs. Figure 33 displays the types of uncertainty sketched here. First, a number of parameters are completely certain: they are constant parameters. For instance, the capital of the environment is constantly zero (drawn in the left graph in Figure 33). This is correct, because the environment is modelled as an agent. In the model it is assumed that agents have capital. This specific agent however, cannot pay and never gets paid. As a consequence, the capital should be constantly zero and the outcome suffices.

Second, some parameters have increasing uncertainty. Mainly scenario trends follow those patterns. For instance, it is found that the coal price gradually rises with increasing uncertainty. That uncertainty resides within small ranges (drawn in the middle graph in Figure 33). This is the outcome of the modelled scenario trend, under little stochastic variation. The coal price is used as *input* of the model. Therefore, it is



not an emerging property and uncertainty is bound. All scenario trends, mentioned in paragraph two, are observed to follow the expected patterns.

Third, parameters that represent an emerging systems property follow complex uncertainty patterns. Examples of those parameters are the portfolio composition, the average electricity price, the CO<sub>2</sub> market volume and CO<sub>2</sub> right price are parameters that. The capacity for biomass power plants, thus an indicator for the portfolio composition shows a complex pattern with large uncertainty. That is drawn in the right graph in Figure 33.

The focus of the discussion lies on this third set of outcomes. However, to validate the model, all parameters are visualized to verify that the observed patterns are as expected and can be justified.

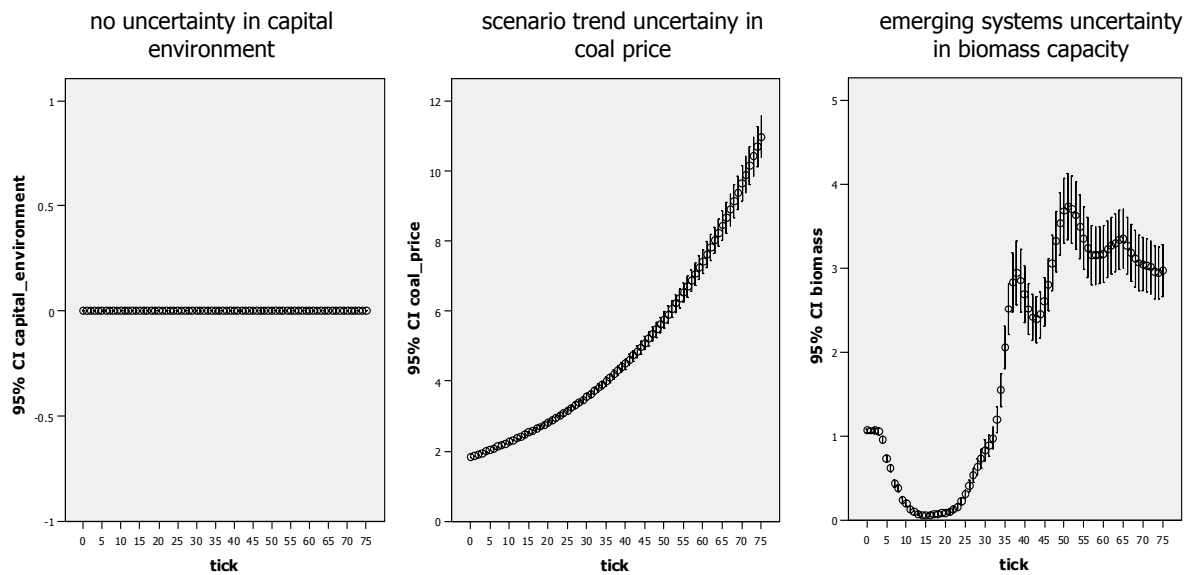


Figure 33. Types of uncertainty in outcomes.

### Uncertainty ranges per scenario

The uncertainty can, as was stated in Table 14, also be measured per scenario (see the examples in Figure 34). Some parameters are constant per scenario, based on the definitions of the scenarios. An example of that is the emission right demand of the industry. In contrast, for many parameters, complete confidence intervals are different per scenario. The trends of the scenarios impact the simulation outcomes. For instance, the scenario axis called world economy growth, determines fuel prices. The capital of the world market is determined by the sold fuels and therefore by those fuel prices. The outcome, displayed in the left graph in Figure 34, is that all scenarios with high world economy growth have the same *confidence interval* of values for capital of the world market. In contrast, the zero scenario, with medium world economy growth has a complete other range as output. In addition, scenarios with low economy growth have a third range of values. The three ranges of values go further apart over time, because over time effects of the trends resulting in these outcomes build up. After 35 years, they are distinct.

Some emerging properties, such as the actual amounts of grandfathered rights, have distinct confidence intervals for all, or most scenarios (see the middle graph in Figure 34). The uncertainty ranges are small for each scenario. For these parameters, the scenario mainly determines the values.

Other emergent properties result in overlapping uncertainty. For instance, the development of the portfolio composition contains such parameters. The values of the amount of wind farm capacity are uncertain and the confidence intervals overlap (see the right graph in Figure 34). The trends, caused by the scenarios are distinguishable by looking carefully, but the uncertainty is too large to claim emerging differences because of the scenarios.

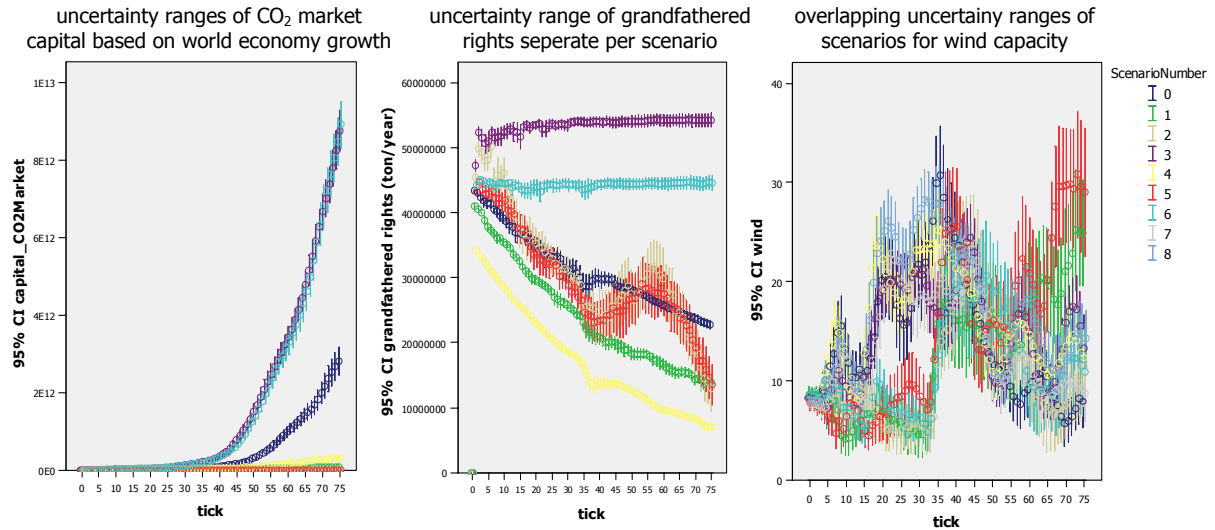


Figure 34. Uncertainty distinguished to scenarios.

## 7.4 Simulation outcomes of CET impacts on electricity generation

In this paragraph, the outcomes of simulations are presented that elucidate the impact of CET on CO<sub>2</sub> emissions, by a change in development of the electricity generation portfolio. First, the reductions in CO<sub>2</sub> emissions are presented. Next, the developments of the electricity generation portfolio are discussed. Subsequently, the generation capacity is discussed. Finally, the electricity prices are presented.

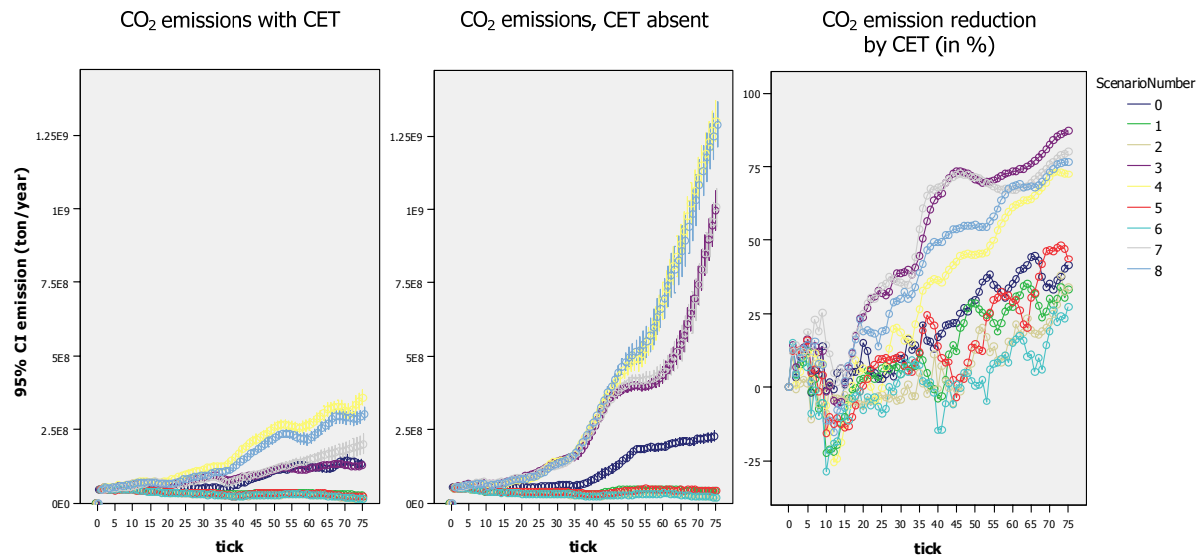


Figure 35. Development of the CO<sub>2</sub> emissions per scenario with and without CET.

### Reductions in CO<sub>2</sub> emissions

The simulated amounts of CO<sub>2</sub> emissions are presented in Figure 35. In the scenarios, under which the demand for electricity rises (scenarios 0, 3, 4, 7 and 8), CO<sub>2</sub> emissions increase: absolute reductions are not achieved over time. In the worst scenarios, with large economic growth, the emissions caused by electricity generation rise from 50 to 250 Mton during the simulation period. In spite of the absolute emissions, the impact of CET in those scenarios is huge. By comparing the emissions in the simulation with CET installed and when CET is absent, it is found that in the end of the simulation period, electricity generation emission reductions by CET are as much as 70-80%. In contrast, in the first twenty years,

emission reductions are absent. An increase is even found in this period. The reason for this will be discussed later this paragraph. It is concluded that the impact of CET on electricity generation increases over time.

Under low economic growth, emission reductions are achieved as well. The emissions by electricity generation remain below current levels of 50 Mton. The reductions caused by CET at the end of the simulation period are in the order of 20-40%.

The absolute increase in emissions over time is mainly caused by an increase in electricity demand. In addition, the model assumes that electricity demand is inelastic to changes in the price. Although in reality price elasticity of electricity demand is limited, the impact of CET will also decrease electricity demand. Therefore, the impact is in these outcomes underestimated.

Based on these outcomes, it is claimed that CET leads to a reduction of emissions by electricity generation. Therefore, the first criterion, as discussed in the introduction of this chapter is met. CET leads to emission reductions by electricity generation.

### Development of the electricity generation portfolio composition

Reductions in emissions by electricity generation occur by a change in the composition of the electricity generation portfolio. Figure 36 displays the average developments in the electricity portfolio of simulation runs with CET installed and simulation runs in which CET is absent. The portfolio graphs are normalized to 100%. The impact of CET on the emissions, as discussed above, is the consequence of the impact on the portfolio developments.

In the first half of the simulation period, the found impact of CET on the portfolio is small. During those years, a small shift is noted from natural gas power plant to wind farms, biomass power plants and coal power plants. After that period, the impacts increase and significant differences are observed. When CET is absent, coal power plants are dominant for electricity production. At the end of the simulation period, 60% of the generation portfolio is coal power plants. Mainly natural gas power plants and wind farms complete the domestic electricity generation portfolio. In contrast, with CET, the electricity generation portfolio is more diverse. Coal power plants are only 30% of the generation portfolio. In addition, natural gas power plants constitute 30%, wind farms 20% and biomass power plants 3% of the portfolio.

Within the simulation period, the distribution of the portfolio stabilizes. At longer runs, up to 200 years, this stability is maintained.

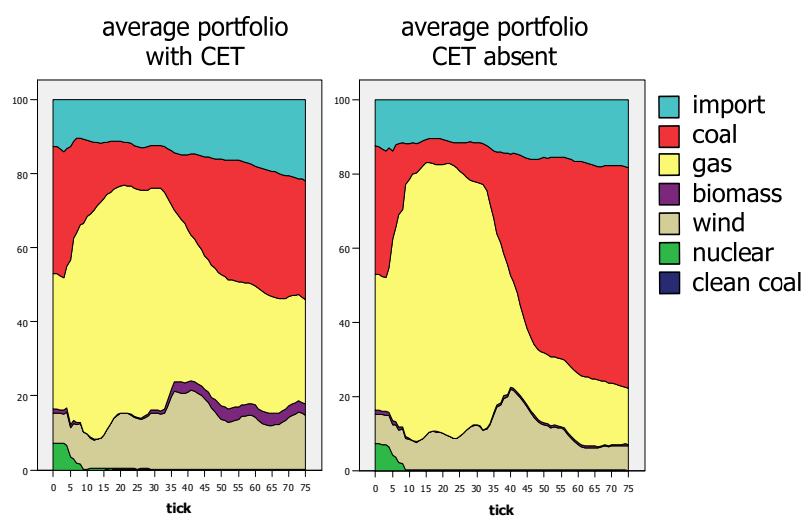


Figure 36. Average development of the electricity generation portfolio.

The impact of CET in the model is a shift from CO<sub>2</sub> intensive coal power plants towards less CO<sub>2</sub> intensive power plants. The delay of this shift is 30-50 years. Because of the shift, natural gas power plants, wind farms and biomass power plants replace 50% of the coal power plants. Note that this change is not only the result of the relative costs of the different electricity generation technologies. It is caused by all criteria used by electricity producers in their investments (profitability, environmentally friendliness, conservativeness, nuclear fear, spatial consumption) and the individual weight factors of each of the producers.

Both the delay in the shift and the speed of the shift observed in the outcomes are impacted by the assumptions of the model. In reality, the *delay* can be shortened by the introduction of smaller units constructed significantly faster than the generation technologies in the model. In addition, although limited, the operational flexibility of existing power plants is in reality used to reduce the CO<sub>2</sub> intensity at shorter notice. For instance, bi-fuelled power plants are more attractive because of the introduction of CET. Furthermore, some installations can be adapted at relatively low costs, without the need for new installations. The *speed* of the shift can be increased by technological innovation. In the model, the impact is simulated on a constant set of electricity generation technologies. However, in reality, the relative attractiveness of power plants also changes by technological innovation. For instance, an increase in efficiency leads to a decrease in CO<sub>2</sub> intensity for CO<sub>2</sub> emitting power plants. Furthermore, innovative generation technologies can the electricity generation portfolio shift to be significantly altered. Finally, the speed of the shift can be increased by exchange of information between electricity producers. In the model, producers have no information on the investments of other parties. In reality, electricity producers make their plans public before the construction is complete. Therefore, the producers have more information to estimate the expected profitability of investments. As a consequence, the speed of portfolio shifts can increase. By way of contrast, the shift can also be slower than observed. Lifetimes of power plants can often be extended at relatively low costs. In addition, as mentioned in chapter four, electricity producers in reality will probably disinvest fewer power plants, because losses are overestimated in the model.

Additional simulation runs showed that the portfolio shift is not significantly impacted if electricity producers count opportunity costs for grandfathered rights as CO<sub>2</sub> costs. Opportunity costs are in reality larger than in the model, for instance by operational flexibility. Therefore, the effect of opportunity costs can be larger in reality. However, no claims can be made based on the outcomes of the model.

It is claimed that electricity producers need operational flexibility of their power plants to prevent a delay of decades. After that delay, even with the current set of generation technologies, CET will lead to a significant shift. The impact of CET is therefore large. Technological innovation can increase the impact of CET and cause a larger shift. CET however does not directly steer at innovation of new market players and further emission reductions can only be achieved by innovative generation technologies.

Different scenarios result in different distributions of the electricity generation portfolio. However, certain scenarios have similar outcomes. Figure 37 displays the changes in portfolio distribution over time for four scenarios. These graphs are normalized as well. As for the average portfolio, stability of the displayed distributions is maintained after the displayed simulation period. Scenarios 5 to 8 are not displayed, because their distributions are comparable respectively to 1 to 4. Consequently, the scenario axis environmental responsibility has no influence on the electricity generation portfolio. Appendix I gives a complete overview of the outcomes with and without CET for all scenarios.

At the end of the simulation period, the impact of CET is largest under high economic growth and stringent external limitations (scenarios 3 and 7). In those scenarios, in which CET changes the dominant power plant type from coal to natural gas. In all other scenarios, CET causes a shift but not changes the dominant power plant type. CET favours biomass power plant and wind farms under large economic growth.

It is observed that in the model, the main differences in the outcome are caused by fuel prices and the demand for electricity. As mentioned earlier, price elasticity of demand is absent in the model. Therefore,

in reality that effect can be less dominant. In addition, the effectiveness of CET depends largely on fuel prices. The impact of fuel prices could even be larger than the impact of CET.

Another observation is that changes in the portfolio distribution are faster when CET is absent. All shifts are steeper. The main cause is that electricity producers estimate the costs for emission rights poorly, because historic data is absent. As a consequence, electricity producers' forecasts are incorrect and decisions not optimal. Therefore, the portfolio distribution under CET adapts slower. This is the main cause for the rise in emission in the first years, found earlier in this paragraph. In reality, predictions of electricity producers are more advanced than in the model. Therefore, this effect will be less in reality. However, also in reality, absence of historic data will result in inadequate estimations during the first decade that CET is installed. Therefore, it is an indication that the third assessment criterion, that no side effects may occur, is not met.

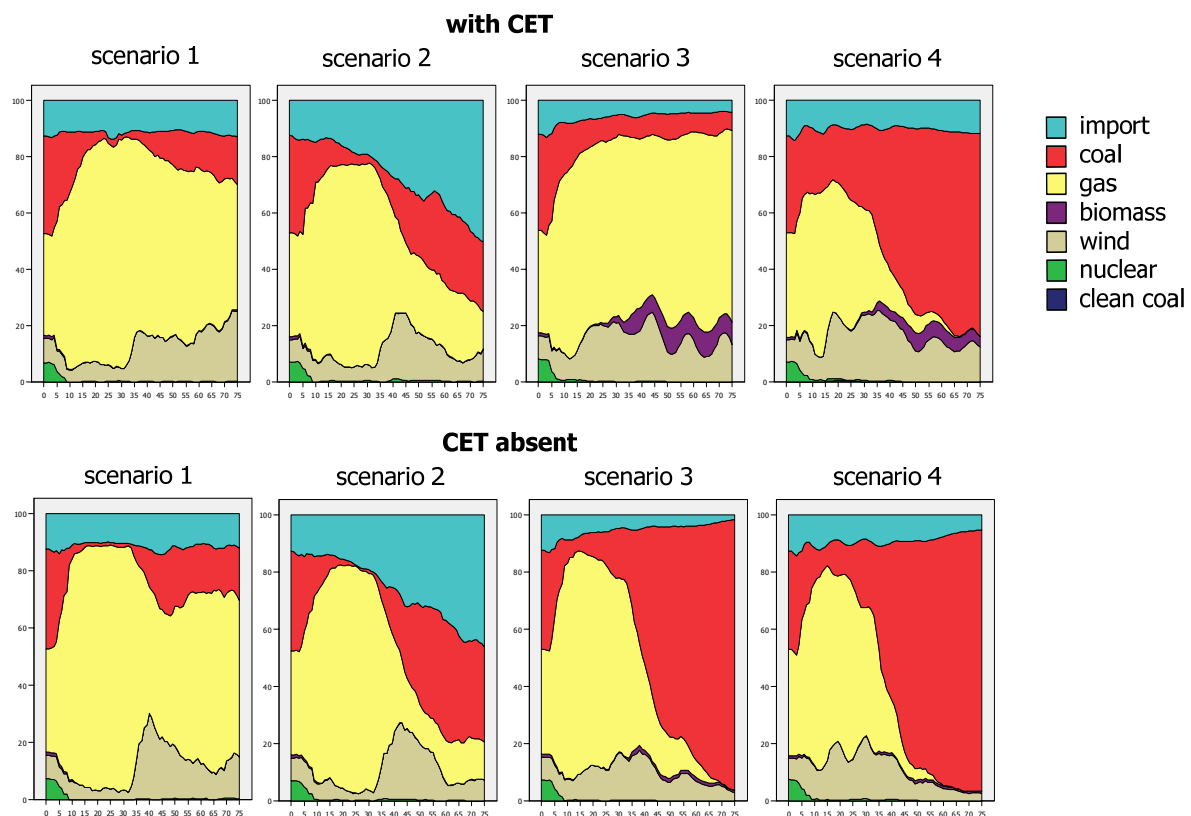


Figure 37. Development of the electricity generation portfolio under different scenarios.

### Development of the electricity generation capacity

Trade on the electricity market is determined by the demand for electricity, which is exogenous in this model. Supply and demand of electricity are highly correlated (coefficient is 0.812, see also Figure 38). Electricity producers look at electricity demand to decide to invest in new capacity.

Stable and gradually rising demand is followed adequately by supply capacity, with or without CET. In contrast, the decision algorithm that electricity producers use to invest cannot follow fast rising demand that occurs in scenarios with high economic growth, such as scenario 3. This is caused by the fact that the demand for emission rights rise. As a consequence, emission costs rise larger than electricity producers expected. Consecutively, CET causes more disinvestment in existing capacity. Therefore, CET decreases the ability to maintain reserve capacity for electricity supply. By comparing the two graphs at the right of Figure 38, it is observed that in the absence of CET, supply capacity is far more adequate then under CET. It must be noted that it is *not* claimed that under high rising electricity demand, supply capacity will not be adequate. The assumptions of this model are too restrictive for that statement. For instance, government could intervene or new players could enter the market under such conditions. In addition, as

mentioned above, disinvestment is overestimated. Consequently, the effect is probably less than observed in the model. However, it is an indication that CET decreases the ability of electricity producers to follow rising demand adequately. Therefore, it is another indication that the third assessment criterion, as stated in the introduction, is not met.

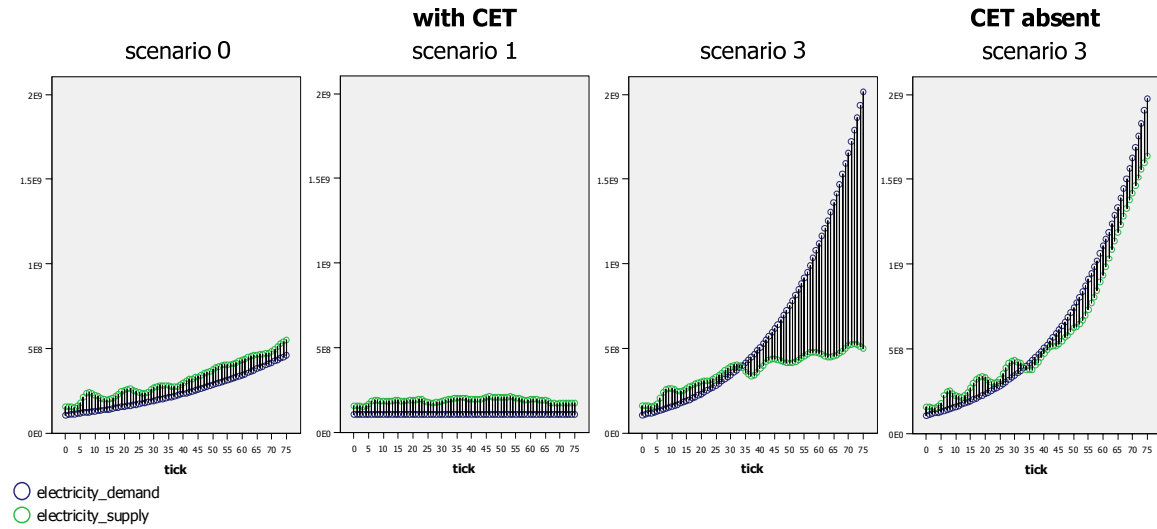


Figure 38. Development of electricity supply and demand in three scenarios.

Under rising electricity demand, investment cycles are found. Waves of capacity with a period of somewhat longer than 10 years are observed as well as (less notable) waves with a larger period of 30 years. It is surprising that they are observed in this model, because they were not modelled. Investment cycles emerge in the dynamics of the system as a consequence of the individual investment decisions of electricity producers, which is fundamentally different from the result of models using traditional modelling paradigms. In those models, the possibility of investment cycles are shown by *explicitly* modelling them. As was discussed in chapter two, the investment cycles in electricity generation occur because of inadequate price signals in this capital-intensive industry with long life times of power plants. Investment cycles in electricity generation are a source for social inefficiency of a liberalized electricity sector. Investment cycles in electricity generation could be affected by CET, because CET introduces a new price signal in investment decisions. However, the investment cycles in simulation all runs were comparable. Therefore, no impact of CET on investment cycles can be claimed.

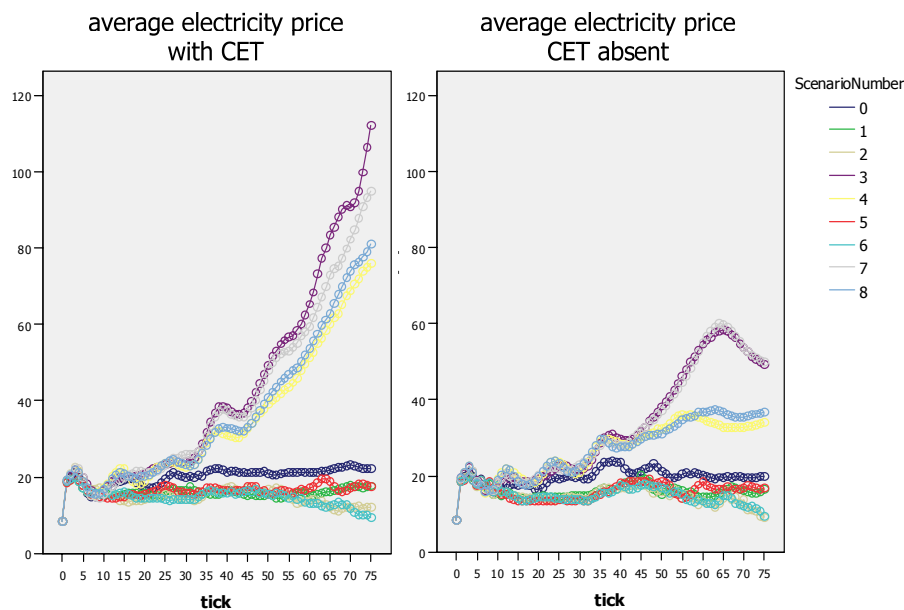


Figure 39. Development of the electricity price per scenario with and without CET.

## Developments in the electricity price

The electricity prices on the electricity market are determined only by supply and demand for electricity, because the market is assumed to function under perfect competition. Maintaining reserve capacity under rising electricity demand is more difficult when CET is implemented. Therefore, market prices are higher with CET. For the other scenarios, no impact could be found. Results per scenario can be found in Figure 39. Price ranges for electricity in €/MWh are drawn per scenario. Electricity prices in reality are more sophisticated than in the model, because the large time step in the model. Therefore, the impact of CET on prices can be less. However, an impact of CET on prices can be expected. Since higher electricity prices may lead to lower electricity demand, an impact of CET on the demand for electricity can be expected. However, that effect is not substantiated with this model.

## 7.5 System level outcomes on the CO<sub>2</sub> emission right market

In this paragraph, simulation outcomes related to the CO<sub>2</sub> emission right market are discussed. The rights on this market are non-grandfathered rights, surplus of other sectors or other countries or are the result of the exploitation of JI/CDM projects.

Under low economic growth, the actual emissions are within the capped amount specified for the electricity sector. Additionally, when external limitations are low (scenarios 2 and 6), the grandfathered rights suffice for electricity generation (see the middle graph in Figure 40). Consequently, CO<sub>2</sub> costs are absent as well as the impact of CET on electricity generation, but actual emissions remain within the cap on the emission rights for electricity generation. Under stringent external limitations (scenario 1 and 5), the market is used to buy CO<sub>2</sub> rights for electricity generation (see the left graph in Figure 40). Although the cap is declining under these scenarios, actual emissions remain within the capped amount at least for the first 40 years. Uncertainty after that period increases.

In the other scenarios with large economic growth (3, 4, 7 and 8), the emissions are not reduced to the amount capped for the electricity sector. After the first 10 years, market volumes are observed to be able to emit CO<sub>2</sub> beyond that capped amount (see the right graph in Figure 40).

The average electricity price is correlated with the CO<sub>2</sub> price and volume on the market (both in €/year and in ton/year). It is observed that high electricity prices and CO<sub>2</sub> market volume occur in the scenarios with high economic growth.

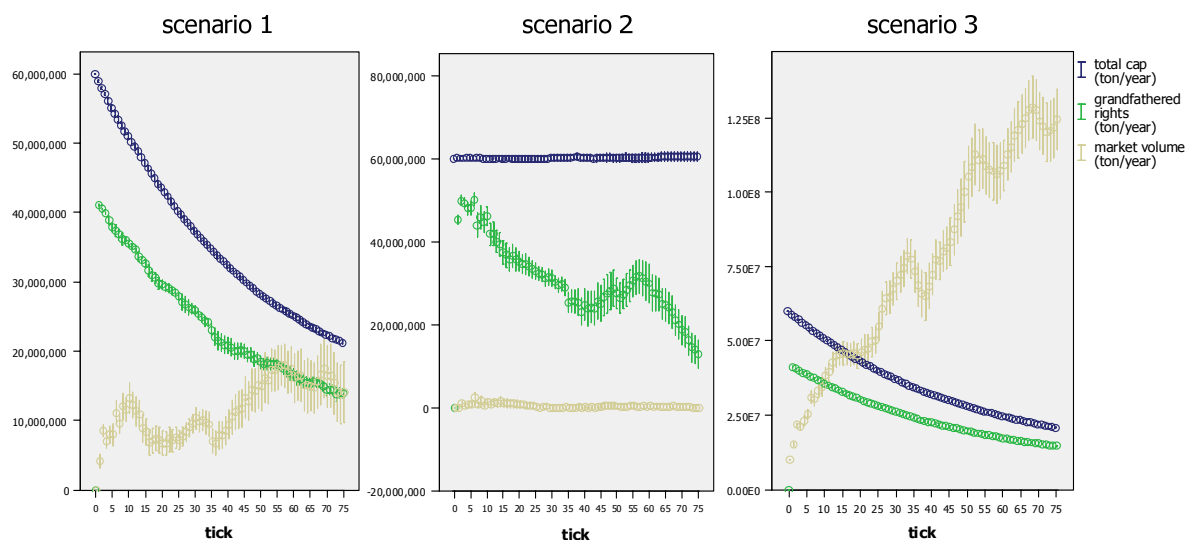


Figure 40. Development of CO<sub>2</sub> market volume and cap in three scenarios.

CET will probably not lead to emission reductions by electricity generation to the allocated cap for this sector. This implies that change in the composition of the portfolio of the electricity sector on the long term does not lead to reduced emissions as expected by the government. This is the outcome of the



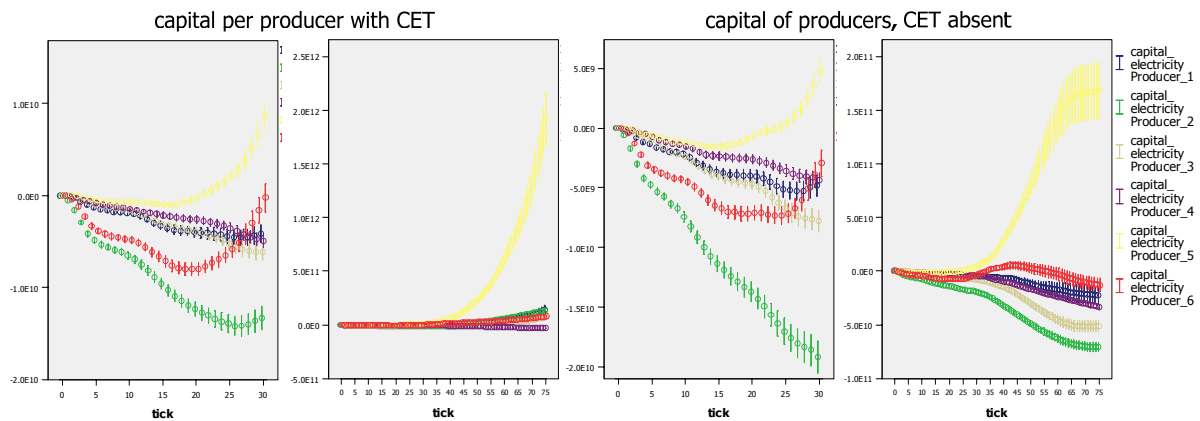
individual strategies chosen by electricity producers. Those strategies are chosen in spite of high emission costs. Only under low external limitations and low economic growth, the cap is maintained during the complete simulation period. However, under those conditions, the impact of CET is absent. Therefore, the reductions are not achieved because of CET. Emission rights therefore need to come from reductions in other sectors or other countries. The achieved emission reductions can still be an efficient outcome, although the emission reductions by electricity generation are not to the cap for that sector. However, that means that CET might not be the right instrument for reducing emissions by electricity generation. In addition, the electricity sector depends on rights available from other sectors and countries. That is problematic when the other involved sectors and other countries also have shortage of rights. Because those sectors are not modelled yet, the total impact is not yet quantifiable. Based on the findings, the second assessment criterion, that emissions by electricity generation should be reduced to the imposed cap for that sector, is probably not met.

## 7.6 Individual level outcomes of the electricity producers

The previous paragraphs discussed the outcomes on the system level. This paragraph presents the simulation outcomes of individual electricity producers. Using the agent-based modelling paradigm, management styles and market positions were introduced in the definitions of electricity producers. Consequently, each producer and its decisions are unique. Details on the management styles and market positions can be found in Appendix D. In this paragraph, first the economic performance is discussed. After that, the composition of the individual portfolios are discussed, in other words, the types of power plants that each electricity producers owns.

### Economic performance of electricity producers

The economic performance of the electricity producers differ (see Figure 41). Although the starting point is equal, even in the first years, differences are found between the producers. The agent-based model lacks the level of detail needed to claim these results as exact capital flows. However, relative performance between electricity producers as well as the impact of CET on those performances are relevant. First, the results are presented for the first simulation period of 30 years. Subsequently, the results of the second simulation period, up to 75 years are discussed.



**Figure 41. Development of capital of electricity producers over 30 and 75 years, with and without CET.**

In the first 15 simulated years, the financial position of electricity producers decreases. By way of contrast, in the second 15 years, some of the producers (electricity producer 5 and 6) are able turn that trend. In addition, within the first 30 years, electricity producer 5 made up all losses. During the same period, a small impact of CET is observed: All electricity producers perform better under CET. The most notable impact of CET is on electricity producer 2: only with CET, the downward trend is stopped after 25 years and profits are made after that. As mentioned before, exact capital flows have no meaning, since profits and losses are overestimated. In addition, costs and revenue are not as sophisticated as in reality. The bad performance in the first 15 simulated years is probably caused by the fact that the initial portfolio distributions are not optimal for the agents in the simulation. The producers are able to increase their economic performance by adapting their portfolio. This effect is only apparent in the first half of the

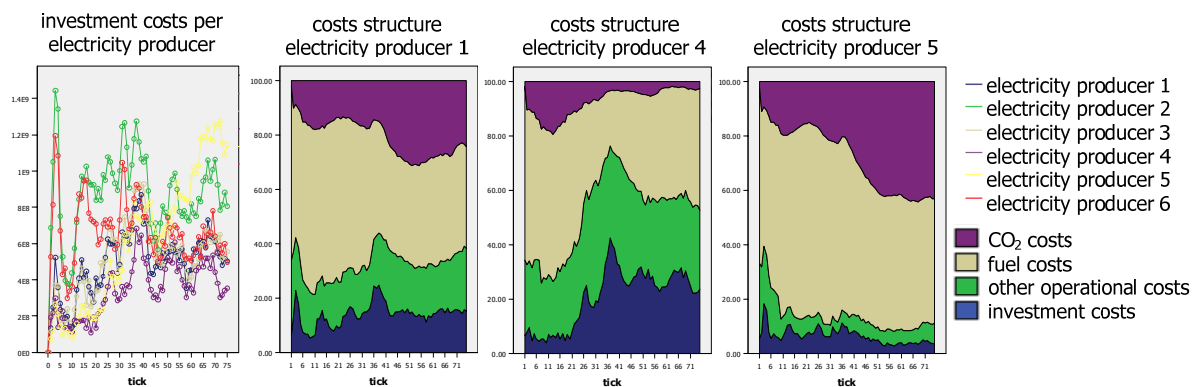


simulation. It is concluded that, during the first 30 years, CET affects the *absolute* capital flows: all electricity producers perform economically better. This is caused by higher revenues from selling electricity. In contrast, no claims can be made on the impact of CET on the relative performance of electricity producers during this period.

In the second period, the last 45 years, the economic performance of the producer deviate more. Electricity producer 5 performs extraordinary well compared to the other producers. This producer was the best performer in the first period as well. The performances of the other producers stabilize. The impact of CET on this term differs from the impact noted above. Also on the long-term, the economic performance of producers is much better under CET. However, the performances of electricity producers, except for electricity producer 5, converge more under CET. In other words, the differences are large when CET is absent. In addition, the worst performer without CET, electricity producer 2, performs second best under CET. Therefore, on the long term, not only the extra revenues by selling electricity are apparent. In addition, CET significantly affects the costs for electricity generation. CO<sub>2</sub> therefore must be significant relatively to the other costs. On the long-term, CET affects the absolute as well as the *relative* performance of electricity producers.

The differences between the electricity producers are in the model caused by their management styles and market positions. In addition, the differences are enlarged because the profits and losses are overestimated. The economically best performing agent, electricity producer 5, is a risk-taking agent, an agent that invests and disinvests early. In addition, his supply bids are low. His choice for power plant is modest: all the criteria are evenly weighed. The bad performance of electricity producer 2 is caused by its risk averse management style and market position. This producer invests late, only disinvests after nine years of continuous loss and is conservative. Therefore, the process of structural changes is slower than for other producers.

As was mentioned above, the improved performance of all electricity producers is caused by the impact of CET on the electricity prices. Electricity prices are higher because of the introduction of CET, because the ratio of supply and demand is altered. The increase in revenue is caused by this increase in electricity prices. Since the increase in revenue is larger than the increase in costs, the economic performance of producers improves by the implementation of CET. Consumers pay the increase in revenue: their costs rise together with profits of electricity producers. In other words, financial means are redistributed. It is debatable whether this impact is preferred. As a consequence, the redistribution of financial means are an indication that the third assessment criterion is not met.



**Figure 42.** Costs over time for the electricity producers.

By looking carefully at the investment costs on average paid *per producer* over time, investment cycles are noted for all individual electricity producers (see left graph in Figure 42). Note that these graphs are the average values over all simulation runs. Peaks in the average investment costs are observed with a period of ten years and a period of thirty years. These findings coincides earlier observations this chapter: investment cycles occur both on the individual level and on the system level. The invested amounts differ

between the electricity producers and it is found that no dominant management style and market position parameter determines this outcome.

The developments of the proportions of the costs types of three electricity producers are displayed in Figure 42. These graphs visualise the trade-off between the four types of costs: CO<sub>2</sub>, fuel, other operational and investment costs. Different electricity producers make the trade-off differently. Most producers have costs proportions comparable to electricity producer 1. By way of contrast, two electricity producers stand out: producer 4 and 5 are different from the others. Note that the investment cycles are observed in these diagrams be noted as well. For most producers (1, 2, 3 and 6), fuel costs are dominant, but over time, the ratio of costs for CO<sub>2</sub> rights increases from 10-20%. For these producers the ratios of the four types of costs are most equal. In contrast, the proportion of CO<sub>2</sub> costs of electricity producer 4 is small. Especially, in the second half of the simulation period, in which the impact of CET is larger, the ratio of CO<sub>2</sub> costs declines to below 5%. In return, the investment costs and other operational costs have larger fractions. This is caused by the environmentally friendliness of this producer. The other exception is electricity producer 5, for which the fuel costs are dominant and on average constitutes 50-60% of the costs during the whole simulation period. CO<sub>2</sub> costs play an increasing role for this electricity producer by growing over time from 10% to 40%. This producer minimizes investment and other operational costs. Since the profit of this electricity producer is largest (see above), the economic optimal strategy is one in which most CO<sub>2</sub> costs are paid and thus the largest emission is produced. However, this strategy contrasts the reason for the implementation of CET.

Based on these findings it is concluded that the autonomous responses of electricity producers to CET deviate from each other. Different strategies are used that result in different ratios of investment, fuel costs, CO<sub>2</sub> costs and other operational costs. However, the set of real world strategies is unknown. Although market players together determine the outcome, one single player can be dominant. The model shows that the most profitable strategy for electricity producers is the strategy that results in the largest emissions. Because in reality players can enter and exit the market, it can be assumed that players will be on the market that execute the most successful strategies. In addition, players in reality learn and improve their strategy based on their findings. Therefore, more players will follow optimal strategies. However, in reality, the dominance of players on the market is also determined by other factors, such as their financial position, their market power, and their image. Therefore, the effect of the strategy of market players may be less dominant in reality. However, the optimal strategy is one with large emission costs.

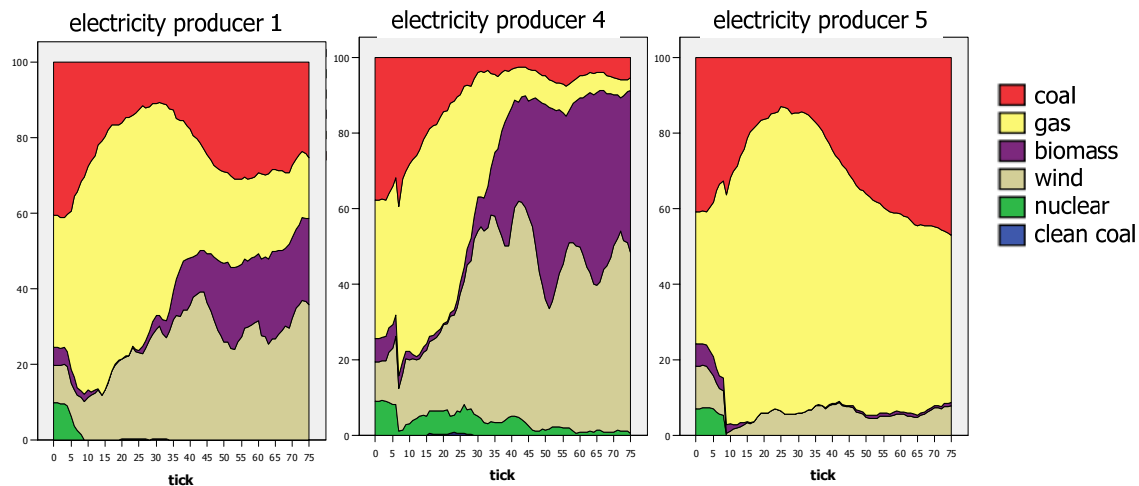
### **Portfolio development of electricity producers**

The investments that the different producers make differ not only in size but also in types of power plants. On average, the electricity producers all start with the same electricity generation portfolio composition. Before the simulation starts, power plants are at random distributed among the electricity producers, such that the distribution of all electricity producers together coincides with the composition of the Dutch electricity generation portfolio of 2004. As a consequence, the individual electricity generation portfolio on average corresponds with the Dutch electricity generation portfolio as well.

The portfolio developments are related to the proportions of costs, mentioned above. As for the costs fractions, electricity producer 1, 2, 3 and 6 have comparable portfolio developments. Only electricity producers 4 and 5 stand out. The average electricity generation portfolio development under CET are displayed in Figure 43. As mentioned above, on average, the starting point is equal. In contrast, the developments deviate. See Appendix I for a complete overview of the developing portfolio per electricity producers, with CET and when CET is absent.

As mentioned above, most electricity producers develop portfolios comparable to electricity producer 1. After a period of coal and gas dominance, a diverse and balanced portfolio emerges of coal, gas, biomass power plants and wind farms. Clean coal and nuclear power plants are not built. By way of contrast, outcomes for electricity producer 4 and 5 are different. Electricity producer 4 is more environmentally friendly. The same dominance of coal and gas characterises the first decades. However, after 30 years, biomass power plants and wind farms are each constitutes 40% of its electricity generation portfolio composition. In addition, electricity producer 4 is the only developer of nuclear and clean coal power plants. The costs structure found above corresponds with these findings and, on the longer term, this

portfolio is even economically attractive. However, the most dominant electricity producer is electricity producer 5. It is economically the best performing producer, but also the producer that causes most emissions. Its portfolio mainly contains gas and coal power plants. In addition, electricity producer 5 has the largest portfolio of all producers. As a consequence, the total portfolio is most similar to electricity producer 5 and the other electricity producers have less impact. The role of environmentally friendly power plant types therefore is little, although 5 of the 6 producers invest in them.



**Figure 43. Development of the electricity generation portfolio for electricity producers with CET.**

As was mentioned earlier, the strategies electricity producers choose can change over time. It is found that the most effective strategy under CET is one with an electricity generation portfolio causing large emissions. If it can be expected that such a strategy is adopted by current or new market players, the effectiveness of CET in reducing emissions by electricity generation is probably insufficient. However, the effectiveness of the impact of CET largely depends on the set of strategies adopted by players on the market.

It is concluded that the individual management styles and market positions of the electricity producers are relevant for the total portfolio. The *combinations* of management styles and market positions of the producers together with the exogenous influences determine the electricity generation portfolio and emissions and thereby the effectiveness of the impact of CET on the emissions.

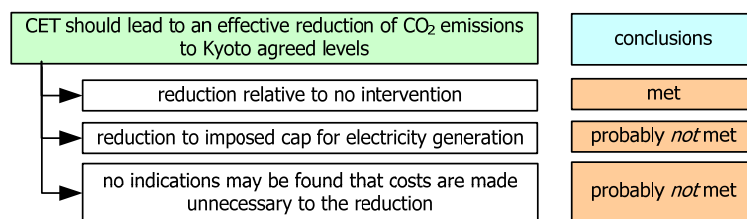
## 7.7 Conclusions

Three sets of parameters are the input for the simulation runs. First, scenarios were developed to represent all relevant exogenous factors. Second, sets of parameters were constructed that define management styles and market positions of electricity producers. Third, power plant specific properties were defined.

The three criteria of CET in relation to electricity generation and the conclusions are summarized in Figure 44. The model build in the second part II of this thesis was used to assess the effectiveness of CET on those criteria. CET leads to a reduction in emissions relative to no intervention. This reduction is large: at the end of the simulation period, emissions under CET are found to be 25-80% lower than when CET is absent. In contrast, emission reductions in the first two decades are absent. The impact of CET is a shift from CO<sub>2</sub> intensive coal power plants towards less CO<sub>2</sub> intensive power plants. Because of the shift, natural gas power plants, wind farms and biomass power plants replace 50% of the coal power plants. This shift is in the simulations delayed for 30-50 years. The impact in the first decades will probably be larger, because of operational flexibility and the possibility to invest in small units that can be operational at shorter notice than modelled. In addition, the impact will be larger because of some level of price elasticity of electricity demand and through efficiency improvements and innovative technologies.

It is probable that CET will not lead to the reduction to the amount capped for the electricity sector. The impact of CET grows over time, but because demand rises, achieving emission reductions to the imposed cap becomes increasingly difficult. Therefore, the need for emission rights from other sectors and countries increases. It is debatable whether that is the preferred impact of CET, since rights from other sectors can be scarce as well.

The imposed reduction during the complete simulation period is only achieved under low world economy growth and low external limitations. However, under those scenarios, the impact of CET is lowest of all circumstances and reductions would be achieved without CET as well. In contrast to this result, the impact of CET can be significantly larger if (not yet modelled) innovative technologies can commercially be adopted. However, CET has no direct impact on innovation by electricity producers. In addition, CET would be more effective if electricity demand is more elastic to changes in price.



**Figure 44. Results of effectiveness on assessment criteria for CET impacts.**

Several side effects of CET are observed that indicate costs that are made unnecessary to the reduction. First, under CET, the adequacy of generation capacity is less, because disinvestment occurs more often. That effect is overestimated in the model, but could be significant in reality as well. Second, as a consequence of a decreased adequacy of generation capacity, higher electricity prices are found under CET. Third, when CET is absent, portfolio shifts are faster, because of inadequate the price signals for CO<sub>2</sub> emission rights. In reality, electricity producers probably adapt faster, but historic prices are absent and prices to be expected are unknown. Finally, it is found that profits of electricity producers could rise because of the introduction of CET. It is debatable whether the redistribution of financial means from consumers to electricity producers because of CET can be justified.

The individual management styles and market positions of the electricity producers cause differences in individual costs types proportions as well as differences in the individual electricity generation portfolio compositions. The dominant electricity producer exploits the economically optimal strategy. However, that is also the largest emitter of CO<sub>2</sub>. In reality, differences between electricity producers are larger, for instance because of their financial positions. In addition, new entrants can have other strategies and current market players can adapt their strategies. It is observed that the effectiveness of the impact of CET depends on the set of strategies adopted by players on the market. Although resulting in large emission costs, the optimal strategy may lead to larger emissions.

## 8 Conclusions and recommendations

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### 8.1 Introduction

CO<sub>2</sub> emission trading (CET) is implemented in order to reduce CO<sub>2</sub> emissions. In this system, a party has to own a right to emit an amount of CO<sub>2</sub>. Electricity production is one of the activities for which it is necessary to own permits for emitting CO<sub>2</sub>. CET introduces a new type of costs on the production of electricity. On the other hand, emission rights can be sold if they are not needed. In the currently liberalised electricity sector, autonomous electricity producers individually make operational and strategic decisions. The additional costs caused by CET may lead to a shift in production techniques, due to the influence on the investment decisions of autonomous electricity producers. Insight into this impact is needed, because of the dependence of society on reducing CO<sub>2</sub> emissions, as agreed upon in the Kyoto agreement.

The main question for this research was stated in the first chapter:

*How can the effect of CO<sub>2</sub> emission trading (CET) on the CO<sub>2</sub> emissions, caused by a change in the composition of the Dutch electricity generation portfolio, be elucidated with a simulation model?*

In the first part of this report, CET and the electricity generation were explored. Subsequently, agent-based modelling was selected as modelling paradigm. In the second part, the model was presented as well as implementation and validation issues. In this part, in the previous chapter, the simulation outcomes were presented. In this chapter, conclusions of this research are presented and recommendations are given for future work.

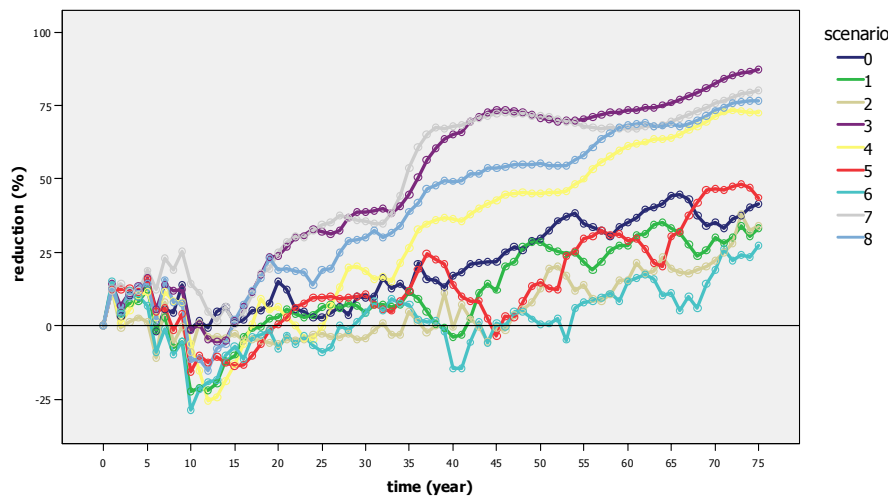
### 8.2 Conclusions

Criteria were derived to test the effectiveness of CET in reducing emissions caused by electricity generation. The first criterion is that CET should lead to emission reductions relative to no intervention. Second, reductions should remain within the set cap for electricity generation. Finally, no indications may be found that costs are made unnecessary to the emission reduction.

Agent-based modelling is chosen as modelling paradigm to assess the impact of CET on electricity generation. In that paradigm, decision rules of autonomous *agents* are the central object of study. The actual impact of CET on the development of electricity generation portfolio is a consequence of the investment and disinvestment decisions of individual and autonomous electricity producers. Therefore, the paradigm fits this problem.

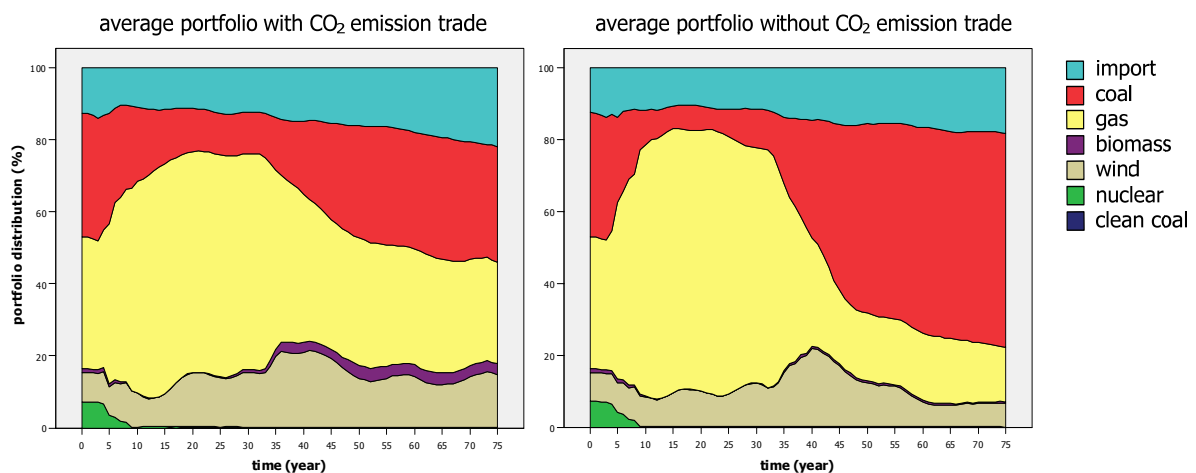
The agent-based model contains a set of agents, representing critical actors, defined by a set of goals, a set of characteristics of the agent itself, a memory of past interactions and a set of rules for interaction. The impact of CET is found by simulating the interaction of those agents under a set of external influences. Possible trends in external influences are modelled as exogenous scenarios. The model contains a number of electricity producing agents that execute operational and strategic actions and a physical system build up of technological installations that are owned by these agents. Agents execute actions that determine the system structure: the electricity generation portfolio is shaped by investments and disinvestments. In addition, the trade of electricity is arranged in contracts. Finally, physical exchange of fuels, electricity and emissions, agreed in contracts, is realized on the level of individual technological installations. Because the system – together with external influences – affect individual actions of agents, the system evolves.

It is concluded that on short term, costs imposed by CET decrease the profitability of power plants that emit CO<sub>2</sub>. However, the impact on operational decisions is small because electricity production installations are bound to the use of specific fuels and the according emission of CO<sub>2</sub>: operational flexibility is limited.



**Figure 45. Emission reductions by electricity generation because of the introduction of emission trade.**

CET leads to a large reduction in emissions relative to no intervention. In the simulations was found that at the end of the simulation period, emissions under CET are 25-80% lower than when CET is absent. In contrast, in the first twenty years, emission reductions were absent (see Figure 45). That impact of CET is caused by a shift from CO<sub>2</sub> intensive coal power plants towards less CO<sub>2</sub> intensive power plants. The delay in that shift was found to be 30-50 years (see Figure 46). Because of the shift, natural gas power plants, wind farms and biomass power plants replace 50% of the coal power plants. That impact is expected to be even larger in reality, because of some of the assumptions underlying the model. The impact in the first decades will probably be larger, because of the operational flexibility of some of the generation technologies. In addition, electricity producers have the possibility to invest in small units that can be operational at shorter notice than modelled. It is likely that the impact on long term will be larger because of price elasticity of electricity demand and through efficiency improvements and innovative technologies. Consequently, CET is an instrument that leads to large emission reductions by a shift in the electricity generation portfolio.



**Figure 46. Normalized portfolio distribution averaged over all scenarios with and without CET.**

Based on simulation runs over a range of scenarios it is concluded that CET leads to large but late reduction in CO<sub>2</sub> emission. In the simulations it was found that at the end of the simulation period,

emissions under CET are 25-80% lower than when CET is absent. In contrast, in the first twenty years, emission reductions were absent. That impact of CET is caused by a shift from CO<sub>2</sub> intensive coal power plants towards less CO<sub>2</sub> intensive power plants. However, the shift occurs with a delay of 30-50 years. In most scenarios, because of the shift, natural gas power plants, wind farms and biomass power plants replace 50% of the coal power plants. The impact of CET in reality is expected to be even larger than assumed in the model. The impact in the first decades will probably be larger, because of the operational flexibility of some of the generation technologies. In addition, electricity producers have the possibility to invest in small units that can be operational at shorter notice than modelled. In the longer term the impact of CET may be larger because of the price elasticity of electricity demand and because of efficiency improvements and innovative technologies.

Although the simulation results indicate that CET leads to emission reduction compared to non-intervention, it is not likely that the emissions are reduced to or below the cap. The main cause is increase of electricity demand. When demand rises, achieving emission reductions to the cap gets increasingly difficult. In the simulations, the emissions by electricity generation are only reduced to its cap under the scenarios in which the impact of CET is lowest of all circumstances and reductions would be achieved without CET as well. In the longer term, significant emission reductions can only be achieved by lower electricity demand or technological innovation. Since CET has no direct effect on innovative behaviour, electricity demand is relatively inelastic to changes price in reality as well as in the model and CET does not affect price elasticity of electricity demand, it appears that CET does not sufficiently reduce emissions of electricity generation.

Several side effects of CET are observed that indicate costs unnecessary to the reduction. First, under CET, the adequacy of generation capacity is less, because disinvestment occurs more often. That effect is overestimated in the model, but could be significant in reality as well. Second, as a consequence of a decreased adequacy of generation capacity, higher electricity prices are found under CET. Those higher electricity prices may lead to higher profits of electricity producers. It is debatable whether the redistribution of financial means from consumers to electricity producers because of CET can be justified. Finally, when CET is absent, portfolio shifts are faster, because of inadequate the price signals for CO<sub>2</sub> emission rights. In reality, electricity producers probably adapt faster.

It is observed that the effectiveness of the impact of CET depends on the set of strategies adopted by players on the market. Although resulting in large emission costs, the optimal strategy may lead to larger emissions. In reality, differences between electricity producers are probably larger than modelled, for instance because of their financial positions. In addition, new entrants can have other strategies and current market players can adapt their strategies. The effect of these aspects requires model expansion and further research.

The chosen modelling approach leads to valuable results for evaluation of the long-term effects of policy and regulation.

### 8.3 Recommendations for future work

Based on the conclusions of this report, recommendations are presented for future work. As mentioned above, it is claimed that CET is probably not effective enough for adequate reduction in CO<sub>2</sub> emissions by electricity generation. Therefore, it is recommended to carefully consider which changes could be made to improve the effectiveness of CET. The successfulness of CET depends largely on exogenous factors, such as fuel prices and technological innovation. Consequently, it is recommended to adapt the system to actual developments. Much uncertainty resides in the future of CET and energy policy in general. This will withhold investments. It is recommended to provide long-term certainty and clarity on policy affecting the return on investments in electricity generation.

More research with an agent-based approach is recommended to acquire insight into changes that could be applied to increase the effectiveness of CET. The model of this thesis should be further developed for that purpose. The most important extensions to the model are enhanced investment decisions (based on discounted cash flow, real options and decision-making under uncertainty), entry and exit of players on the electricity market, distinction between all involved industrial sectors and technological innovation of

power plants. In a later stage, the complete European electricity generation network, with all relevant inter-connectors and country-specific characteristics and regulation can be modelled, in order to get insight in the development of the European electricity generation portfolio.

Next to these recommendations, several developments for the agent-based environment are needed. First, the current agent-based environment opens possibilities to couple top-down aspects and model parts of other modelling paradigms to agent-based models. It is recommended to exploit those options and combine agent-based modelling to system dynamics. For instance, agents in an agent-based model could predict the future by a personalized system dynamics model. A second example is that the external world of the agents is modelled as a system dynamics model. By combining these two paradigms, the strengths of both can be used at the same time. Existing, validated system dynamic models speed up the development process for large models with an agent-based approach. Second, it is recommended to develop validation tools and techniques for agent-based models. Although validity is often claimed, usually, models are only verified to be free from coding errors and are *calibrated* to be valid. Validation by historic data is not always possible and does not lead to conclusive validity. Third, user-friendliness for the modeller should be increased. Developing agent-based models is a complex process in itself, because many aspects of agent-based modelling are not fully developed yet. The environment is not fully equipped with tools regularly available in modelling suites for system dynamics. Many features therefore have to be ad hoc developed during the model development process. Structural developments are needed to build a complete and powerful software package. That would lower the burden to choose for an agent-based approach.

Based on the conclusion that large growth in demand for electricity complicates reducing actual emissions, it is recommended to continue to address the problem of increasing demand for electricity. The focus should not only be on technological solutions that increase efficiency, but also on diminishing demand. As long as private parties are in control of producing and selling electricity to the public, their main goal will *not* be to reduce the actual use of electricity, because that would reduce the continuity prospects of those private parties. As a consequence, governments must take their responsibility and CET should be improved. In addition, since CET is not setup to largely impact demand for electricity, policy should be setup to encourage a decline in energy demand per capita. For instance, this can be done by speeding up the transition process of more efficient end-consumer technology (by making it more attractive or regulating the use of older equipment, such as inefficient fridges and cars). Second, demand should become more elastic on short term. In order to realize more elasticity, consumers must be more aware of their impact. The use of real-time metering in houses can assist if energy prices become significant.

Since innovative electricity generation technologies can increase the effectiveness of CET, it is recommended to stimulate electricity producers and research programs in the development of such innovations. Government should actively undertake actions to find ways to address both issues of the depletion of the natural resources and retaining a stable climate. This research shows that simulation models using an agent-based approach offer a valuable contribution to the evaluation of policy that affects complex systems.



## 9 Model development process

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### 9.1 Introduction

At the end of this report, after the development of a model and the presentation of its conclusions, the process in which that occurs is reviewed. This process was designed as well as the model itself. In this chapter, best practices and trade-offs will be discussed that assist the model development process. They came from the process of the author and from the observations of processes of others modellers. The focus is on the agent-based modelling paradigm. Because this paradigm is not yet used much on problems with that are multi-disciplinary (technical, economic) and large scale, the tools and knowledge available is not always sufficient. This makes the model development process more complicated. In this chapter, solutions for these problems are sought. A distinction is made between trade-offs and recommendations on the one hand and the reflection on the modeller on the other hand. The findings in this chapter can assist in the model development process of future models. They were already applied during the process of this thesis.

### 9.2 Trade-offs and recommendations

This paragraph elaborates on methods and steps that can be used to improve a model development process such as described in this thesis. Those best practices and trade-offs are adopted to improve progress and quality of the results.

#### Conceptualization versus parallelism

During the design of models, the modeller learns more on the concepts he models. However, beforehand you must have a clear starting point. In this thesis, multi-actor analysis, a system analysis and a system decomposition method were used before modelling started. The modeller needs well-defined knowledge on the topic to be able to have a usable starting point for the model development process, but the level of detail needed at forehand can be debated. Because the development process is iterative, different phases of model development overlap. As a result, multiple processes occur parallel. Parallelism increases the modellers inspiration by making analogies between those phases. The idea of parallelism can be extended by working parallel on several topics, issues or in several domains. Additionally, inspiring parallelism can be found in hobbies, such as making music, doing sports and playing family games. This is recommended, because the most inspiring analogies are found in domains far off the actual topic. A trade-off has to be made as explicit as possible between the amount of knowledge that is acquired before modelling starts to be able to model with progress on the one hand and the time it takes extra to focus only on conceptualizing the problem, and not work parallel to increase progress on the other hand.

#### Learning by studying versus analyzing versus doing

To learn the java programming language and the tools used for modelling, three different steps should be taken: studying material, analyzing code and programming proof models. These steps in reality are not separated but will go simultaneously and a trade-off has to be found in these steps. The focus should shift over time from studying, towards analyzing and finally towards writing. These three are now shortly discussed separately.

Studying the java language can be done by browsing through information sources such as books, articles and tutorials. The sources can be used as reference for more experienced programmers. Because the

author of this thesis was not familiar with the java programming language, the following sources were used:

- recommended books by friends and colleagues on the java language (Bishop 1998; Balagurusamy 1999; Eckel 2000; Sierra *et al.* 2005),
- Java API Specification (Sun Microsystems 2006b),
- The Java Tutorial (Sun Microsystems 2006a),
- the repast api (Repast 2006c),
- the repast tutorial (Repast 2006b),
- several manuals.

‘Learning by analyzing’ means studying code of other java developers. If the modeller develops the modelling environment together with colleagues, code of colleagues can be used for analyzing. It is not directly necessary to understand each line of code, but at first only the structure of the code should be understood. Later on, when more detail is needed, specific solutions on how to write specific grammatically correct code is more easily found with the references of the previous step. Sharing solutions found with programming functioning increases progress of the complete group of modellers. Especially when attention goes to generalization of specific solutions, this advantage increases.

The most intense learning method for the java language is writing code. In line with increasing creativity of the process, it is often fruitful to build or adapt simple existing models. It is encouraged to use models from outside the modellers’ domain to get a feeling for agent-based modelling. The author analyzed and adapted a simple agent based model of Igor Nikolic to get acquainted. It was useful to analyze the structure of the model setup and helped structuring the concepts in my models. This also relates to the fact that the first working model should be a simplistic one, not representing all complexity required for answering research questions.

### **Incremental versus iterative design**

A trade-off has to be made between incremental and iterative design. Incremental design is the production of a series of models that are all fully functional and of increasing complexity. Iterative design is a process in which a consecutive step can start while the first has not finished yet. All steps are followed iteratively until the final step. Incremental design is not iterative, it uses fast cycles in which the model advances. Iterative design is not incremental: only one cycle exists that is iteratively completed. A trade-off has to be found between those two extreme design methods, because both has advantages for the modeller.

The main reason to use incremental design is that it is impossible to grasp complex problems. At the same time, that is the reason why modelling and simulation is interesting and helpful in getting insight into the complexity and dynamics of systems related to complex problems. Progress of the design process is important. The successful increase in complexity achievable in a development cycle of a model is limited. In order to have a functional starting point, it must be of lower complexity. In addition, it is more promising to see some working improvements, instead of writing codes for a long time. Furthermore, when the models complexity increases, many conceptual errors cannot be easily found and solved. After a large step, errors are often not discovered and corrected. As a consequence, validation will be difficult or unsuccessful. Small improving steps can each be verified, validated and tested. This can be done by taking extreme values for some parameters and read and interpret outcomes of the model (see also visualization).

The first working model should not be complex at all. A set of restrictive assumptions should be made for a first working model. It is very likely that the research questions cannot be answered because of those assumptions, but it is a necessity to finally be successful. Therefore, it is probably useful to first start focussed on incremental design. Creativity in the selection of the starting point of modelling is essential. Arguments can be given to start with a central concept, actor or subsystem for the observed system. It is scientifically logical to start with the central component your questions are about to be able to show that your model will be able to help you in answering your research questions. Based on the argument above, it is argued that that starting with modelling less complex components is more appropriate. Progress is easier with a less complex starting point. Components at the border are often not as interdependent with

other components and therefore can more easily be implemented. Since modelling itself is a learning process, the modellers modelling abilities increase together with the complexity of the modelling steps. Another solution is to start with an existing model that is somewhere related to the models that the modeller wants to program. By incrementally adapting a working model, a working version always exist which is a continuous driver for progress.

However, a modelling process is fundamentally iterative, because during the development, errors are made, and insight is achieved. When a number of model cycles are done, speed of the incremental design will decrease. As a consequence, iterative design will be advantageous. By using such a process, the robustness of the eventual model will increase. Path dependence and lock-in effects will be less when accepting this iterative character. Thus, a dynamic trade-off between incremental and iterative design is necessary.

In the process for this thesis this, the trade-off was as displayed in Figure 47. The circles represent incremental design. The double headed arrows represent iterative design. On the shortest time scale (minutes to days), small incremental loops were made. Verification of small improvements is directly tested and no iterations to previous steps are done within this time scale. On a somewhat large scale (days to weeks), iterative design was dominant. Results are interpreted which causes finding errors in decisions or gaps in previous steps that need to be corrected. On the highest level (say months), large incremental loops are made. Simulation results, discussions and new knowledge are used to build larger and more complex models.

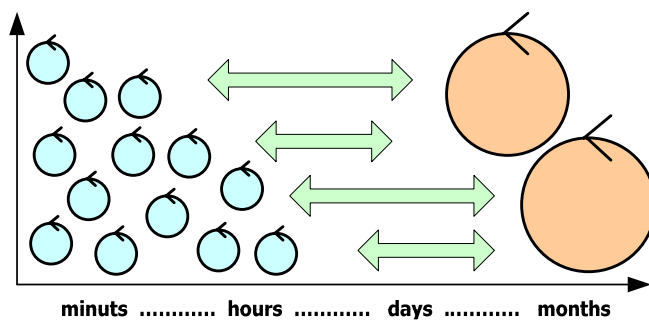


Figure 47. Iterative versus incremental design.

### High versus low abstraction

A main trade-off should be made in the level of abstraction. Too little detail result in irrelevant and invalid outcomes. Too much detail slows the process down. This trade-off must be made explicit. The choice for abstraction can be used in four ways to enhance the model development process.

First, different levels of abstraction can be used in the same model if the choice can be made separate for the different parts of the model. This is the case when subsystems are distinct and systems have subsystems with different time-scales of relevance. An abstract version of subsystems can be modelled that represent the processes relevant for the time-scale of the total system. For example, millisecond control of electricity networks is not of interest when the overall time-scale is one of days or even years. Therefore, a network can be modelled in without millisecond control.

Second, the complexity of a modelling exercise can be reduced by using higher abstraction. An abstract form might be easier to program and can still be adequate for the overall model.

Third, parts of other models, with different abstraction, can be used to speed up the model development process.

Fourth, the modelled can use high levels of abstractness for temporary subsystems. They can be modelled in more detail in a later stadium to use incremental design (see also above). The focus in a model is

implicitly determined in the choices made for abstraction of subsystems. Because this focus is very important, these choices should be made as explicit as possible.

### **Small versus large system boundaries: the use of scenarios**

The system boundary determines which parts of the world are modelled and which parts are not. A priori selection of the system boundary is not necessary. Furthermore, closing the borders is not necessary. Data and trends of data can enter from outside the border, in this thesis by scenarios. For instance, if the processes for price forming of a specific market is not modelled, it might be modelled as a exogenous variable. The modelled agents can react on that given. In open systems, material and data flows can go in and out the system. The system border might change (expand) during the model development process by incremental design. The focus is determined by the selection of the system boundaries.

### **Top-down versus bottom-up**

Top-down and bottom-up modelling are usually different paradigms. Agent-based modelling is traditionally a bottom up approach, but it is recommended to use top-down aspects where applicable. For instance, system dynamics models can be used for scenario development. Another example is regulation, which in the real world at least partly is set up top-down by an agency. By using the best of both worlds, progress can be improved and eventual results more realistic. In the recommendations of paragraph 8.3, more can be found on this topic.

### **Communication and collaboration versus progress**

Both communication and collaboration can help keeping focus in the modelling process. However, communication and collaboration also take time. Therefore, a trade-off needs to be made between the progress of the model development and these two. The trade-off has to be such that both the communication and collaboration help to increase progress instead of slowing the model building process down. Communication helps because making choices often happen when talking about it with colleagues or friends. While forming a sentence, order has to be formed explicitly and low ends of argumentation are tied up. Also presenting preliminary results help in the process of improving models. They are possibilities to get a modeller out of a conceptual loop it has locked in. It should be noted that choices made are never final; there is always a point of return as described as iterative design. Collaboration helps the modelling process to be creative. In addition, synergy effects of several modellers of different backgrounds increase the quality of the result, since no person can know all aspects of the content of the problem and of the agent-based modelling tools. Innovative solutions to modelling problems are more easily found together. Note that collaboration increases the modellers dependency on the other modellers.

### **Visualization for communication versus validation**

Visualization should be used for two goals. First, visualization shows your results to supervisors, problem owners and colleagues. The visualization helps convincing them of the usability and importance of the model. Second, it is a method to verify and validate whether an (incremental) model is working correctly. It is not easy to select parameters that are interesting to display. It depends on the types of questions asked and the purpose of visualization. For validating code, textual messages can be displayed when certain code is processed as well as certain variables and outcomes. Errors can be found more easily by observing textual output of running models than by observing code. However, that output is not communicable to supervisors. It is recommended to create many graphs and continually interpret them. New functionality often leads to the need for new graphs, but also the other way around. Findings from the results displayed in graphs can be used to adapting or enhancing the model.

### **Creativity techniques**

It must be noted that creativity is not only an intrinsic characteristic of a modeller but can also be explicitly used in the model design process. To find new ways to model the complex problems in multi-disciplinary systems such as in this thesis, creativity is necessary for several reasons. First, the use of creativity techniques makes the process more enjoyable, which does help in getting better results. Second, new and innovative solutions can only be the outcome of a creative process. By thinking out-of-the-box, the modeller can apply ideas of other domains into the models. Brainstorm sessions with actors involved can help find new objectives and analogies can help finding problems and solutions. There is a large role

for creativity in visualization. Much more can be found on creativity techniques. Elaborate sources can be found on this topic (e.g. Mycoted 2006). Time and effort should be invested in creativity, even if the results are not directly notable, because the results of creative processes can be unexpected.

### 9.3 Reflection on the modeller

Besides the recommended trade-offs, the modeller needs some abilities and characteristics. In this paragraph, a reflection on those abilities is given.

The most important ability is drive. To be able to survive the challenging journey of creating an agent-based model of a multi-disciplinary problem, one has to make difficult choices and has to face set-backs. The trade-off of incremental and iterative design shows that it is not easy to reach the end of a model development process; the modeller has to find new energy and promising results in small, preliminary models. The modeller must be able to have an accurate perspective on the contribution he makes each day to the process he is in and realize which efforts are necessary for reaching a satisfactory model.

In this type of modelling, the degrees of freedom are huge; choices are almost unlimited. The modeller has to be able to cope with the insecurity caused by that fact. Furthermore, analytical and conceptualization capabilities are needed to grasp these complexities and translate them into a model. A model development process need to be set up to help the modeller in that. However, certain capabilities must be in the modeller. Extensive domain knowledge is needed. The larger the scale of the observed system, the more knowledge is needed from other domains as well.

The modeller must be aware that he or she has to become a programmer. Agent-based modelling have to become more user-friendly, but for now, the modeller builds code. Consequently, the modeller has to be able to conceptualize ideas to code. Affinity for programming is required to be able to successful. The modeller has to be precise to come to a correct set of code.

The modeller has to find support in the process in his team, since many results can be shared. Functionality, model parts and ideas can be exchanged. Drive is found by joining or forming a creative team that stimulates individual results.

Some level of intrinsic creativity is needed to able to get through the complete process. Each model has special characteristics for which individual and creative solutions need to be found. Creativity can be an inspiring source for drive in the process.

### 9.4 Conclusions

Trade-offs have to be made in the model development process. Specific for the development of agent-based models of complex problems in multi-disciplinary systems a number of those trade-offs should be dynamic.

The amount of knowledge that is acquired before modelling starts to be able to model with progress should be explicitly balanced to the time it takes extra to focus only on conceptualizing the problem, and not work parallel to increase progress. To learn the java programming language and the software tools used for modelling, it is recommended that over time the modeller shifts from studying, through analyzing to writing. A dynamic trade-off between iterative and incremental design should be made, in which progress and creativity should be the main criteria. Abstraction levels should be dynamic. The abstraction level can vary between parts of models. In addition, over time abstraction levels can decrease by advancing models. The choice for abstraction is connected to the choice of system boundaries and the use of top-down and bottom-up aspects.

In agent-based modelling, the degrees of freedom are extremely high. The modeller has to have drive, find support in the modellers' team and be creative in order to develop agent-based models of complex and multi-disciplinary systems successfully.



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## Appendices

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## Appendix A. Multi-actor analysis

This appendix, the multi-actor analysis is presented of which the outcomes were used in 2.3. This analysis is based on chapter seven of Enserink, *et al.* (2002). A multi-actor analysis is executed for qualitative insight in a problem, regarding the positions, perspectives, goals and means of all actors involved in that problem. All relevant social goals and risks are included to be able to increase social support. A mono-actor analysis would only include the perspective of the problem owner and the results of a study based on such an analysis might be less supported by all actors involved. The activities in a multi-actor analysis include determination of problem perceptions, goals and interests of the relevant actors. In addition, the possibilities of actors to influence (parts) of the system are considered. The result is more insight in the problem and the place of the different actors.

First, goal trees are made of the most important actors: the government and an electricity producer. Second, an overview of the problem perceptions, interests and goals of all actors involved.

### Goal trees

A goal tree states the various levels of goals of an actor. A goal consists of several lower level sub goals. This appendix displays goal trees for the most important actors: the Dutch government (Figure 48) and an electricity producer (Figure 49).

#### *Dutch government*

The choice to focus on the Dutch government is because it's the problem owner. The research aims at accomplishing one of more of the goals in this goal tree. The goals of reaching a healthy environment, namely high air quality and a stable climate are goals of the Ministry of Housing Spatial Planning and Environment (VROM). Both goals follow EU regulation and the Kyoto agreement. Another goal of the Dutch government is secure electricity supply against low costs.

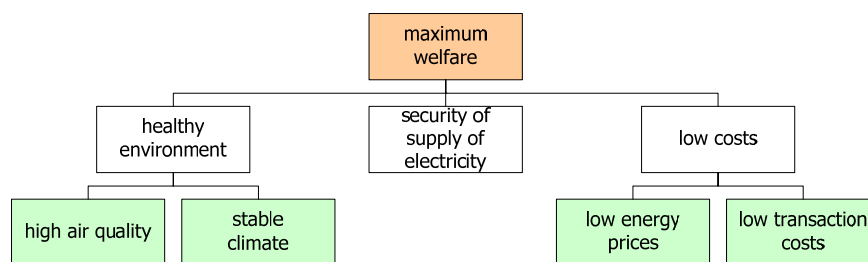


Figure 48. Goals for the Dutch government.

#### *Electricity producer*

The goal tree of an electricity producer in a liberalised market is relevant, because it is the most important player in both the electricity market. In addition, they are large players on the CO<sub>2</sub> market. In order to accomplish the main goal, continuity, higher energy prices and a larger market share increase the revenue. Relevant costs are investment costs, fuel costs, costs for CO<sub>2</sub> rights and other operational costs. Finally, a stable market is a goal of electricity producers, because it decreases uncertainty in the decision-making.

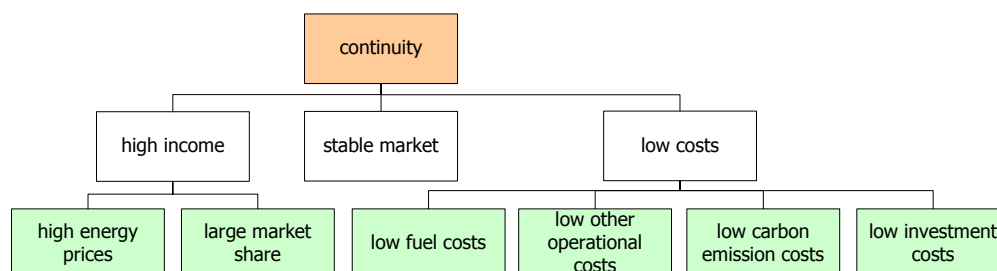


Figure 49. Goals for an electricity producer.

## Overview of actors

The different actors involved in CET are classified in three groups: governmental parties, private parties and other types of actors (such as societal organizations and individuals). The goals and interests differ between actors, causing different perceptions of the problem. Table 15 presents an overview of all the actors involved.

**Table 15. Actor overview.**

actor	problem perception				interest	goals
	criterion	main problem	causes	influences		
EU commission	expected reduction in emission total costs increase for society	without an emission trade system the needed emission reduction to prevent further climate change is not reached	economic developments lead to an increased rather than a decreased emission	(in)direct regulation subsidy regulation agenda setting financial power lobbying power	maximizing welfare of EU civilians	reduced emission of carbon dioxide to Kyoto agreed levels costs effectively
Ministry of Housing, Spatial Planning and Environment (VROM)	expected reduction in emission security of supply of electricity sector	the needed emission reduction must be solved but security of supply is possibly affected	economic developments liberalisation of electricity sector	direct regulation subsidy regulation supervision agenda setting financial power lobbying power	maximization welfare Dutch civilians	reduced emission of carbon dioxide to Kyoto agreed levels security of supply
Ministry of Economic Affairs (EZ)	expected reduction in emission total costs increase for society	without an emission trade system the needed emission reduction to prevent further climate change is not reached	economic developments lead to an increased rather than a decreased emission	direct regulation subsidy regulation supervision agenda setting financial power lobbying power	maximization welfare Dutch civilians	reduced emission of carbon dioxide to Kyoto agreed levels costs effectively
provinces	security of supply	probability of reduced security of supply of electricity	EU and national government created a liberalized market	agenda setting lobbying power financial power	maximization welfare civilians of province	reduced carbon dioxide emission following regional targets
municipality	security of supply	probability of reduced security of supply of electricity	EU and national government created a liberalized market	agenda setting lobbying power financial power	maximization welfare civilians of municipality continuity	reduced carbon dioxide emission following local targets enhance market position
chemical industry	profit efficiency market share market strength security	additional costs additional complexity for decision making	EU and national government created goals of reducing carbon dioxide emission	market power financial power research and development strategic behaviour		
electricity producing companies	profit efficiency market share market strength security	additional costs additional complexity for decision making	EU and national government created goals of reducing carbon dioxide emission	market power financial power research and development strategic behaviour	continuity	enhance market position
environmental organizations	environmental impact climate change	climate change and environmental impact impose health problems for society and nature	economic developments lead to an increased rather than a decreased emission	consumer surveys research lobbying power media power protest power	a healthy environment	no climate change low environmental impact
consumers organizations	tariffs security of supply	electricity prices are possibly rising security of supply of electricity are at stake	EU and national government created a liberalized market	consumer surveys research lobbying power media power protest power	maximization of welfare of Dutch civilians	fair electricity tariffs
civilians	tariffs	electricity prices are possibly rising	EU and national government created a liberalized market	group in protest choose between suppliers shutdown of parts of network lobbying power strategic behaviour	maximization of own welfare continuity	low electricity tariffs stable network
system operator electricity sector	network stability	additional complexity in maintaining stability network	EU and national government created a liberalized market	shutdown of parts of network lobbying power strategic behaviour		
Nationale Emissieautoriteit (NEa)	efficiency possibilities for cheating	no problem	no causes	lobbying power direct regulation impose sanctions	healthy carbon dioxide market continuity	healthy carbon dioxide market
large end consumers of electricity	tariffs	electricity prices are possibly rising	EU and national government created a liberalized market	lobbying power market power choose between suppliers strategic behaviour		low electricity tariffs making profit
trade companies	amount of profit	no problem	no causes		continuity	

## Appendix B. Power plant data calculations and sources

A power plant is modelled as a black box with inputs and outputs. The inputs and outputs are modelled as flows. In addition, power plants convert energy in order to generate electricity. The main properties of the power plants types used in the agent-based model are discussed. After that, calculations and data sources are given for the operational configuration – the input-output structure – of the power plants.

### Main properties of power plants

The main properties of power plants are lifetime, maximum capacity, construction time, construction costs, operational costs and the area of land that the power plant uses (see Table 16). Because most values on these properties cannot be found in publicly available data sources, rules of thumb and expert estimations were used to quantify these data.

**Table 16. Main properties of power plants.**

<i>type</i>	<i>lifetime</i> [year]	<i>maximum capacity</i> [MW]	<i>construction time</i> [year]	<i>construction costs</i> [€/MW]	<i>operational costs</i> [€/MWh]	<i>area</i> [m <sup>2</sup> ]
nuclear	40	550 – 2000	3	2,000,000	5	150
CCGT	30	1000 – 2250	3	500,000	2	70
CFSTP	30	1000 – 2000	3	1,250,000	3	100
wind	25	100 – 2250	3	1,150,000 $\times$ 2	3	100
clean coal	30	1000 – 2000	3	2,000,000	10	200
biomass	30	100 – 225	3	1,250,000	4	100

#### *Lifetime*

As in reality, the lifetime of a nuclear power plant is longest. A wind farm has the shortest lifetime. The other types of power plants have an intermediate lifetime.

#### *Maximum capacity*

The maximum capacity of the plants is a range of *possible sizes*. The ranges were given by expert estimations (Dijkema 2006). The maximum capacity of wind farms and biomass plants can be the smallest. Biomass power plants are always small, but wind farms can, as they are modular, also be very large. Coal and gas plants are typically large. Nuclear power plants can be a bit smaller but can be as large as those two types.

#### *Construction time*

The construction time is for all power plants modelled equal, because no reliable differences in values were found. Using this construction time is necessary to show the delay after the decision to invest in a power plant.

#### *Construction costs*

Some construction costs come from unreliable data sources and were checked by expert estimations to be reasonable. Investing in a nuclear power plant is very costly, because of the needed security measures. Clean coal power plants are as expensive, because their not yet fully developed yet, part of the process is still not yet been done in the world. A biomass and coal power plant have medium costs, they need the same equipment to burn solid fuels. A wind farm has quite low investment costs, but its capacity is not available at all times, because of the dependency on medium wind speed. The model assumes that capacity is always available. Only for wind farms this is insufficient. Therefore, the investment costs are multiplied by two. The gas power plant is cheapest, because the technology is fully developed and gases are combusted.

#### *Operational costs*

The operational costs are the other variable costs than fuel costs and costs for CO<sub>2</sub> rights. The figures are estimations, because data were not found. A nuclear power plant has to deal with the waste that is a costly operation. Consequently nuclear power plants have high operational costs. A wind farm needs intense

maintenance with accordingly high operational costs. The clean coal power plant has to put a CO<sub>2</sub> stream into the ground, which is a very costly procedure. It is said to cost 30 €/ton CO<sub>2</sub>. This means that for 1 MWh produced electricity that produces 0.9 ton CO<sub>2</sub>, so the estimation of 30 €/MWh for the total operational costs is low. It is however expected that these costs drop due to research and development. Therefore, this figure is underestimated. The coal and biomass plant have low operational costs. Lowest operational costs are for gas power plants, because no solid fuels are involved. As a consequence, cleaning is more easy.

### *Area*

The consumed area of a power plant differs and this becomes interesting if available sites are scarce, as in The Netherlands. Consequently, the differences between the amounts of room various power plants use are relevant in investment decisions in the model. Relative estimations are used, because data was unavailable.

The nuclear power plant uses a relatively large area, because of the needed security measures. The clean coal power plant needs the same amount of room, because they have to be near an (empty) gas field. The number of potential sites are therefore small. The gas power plant is the smallest and coal and biomass power plants a bit larger. Wind farms are initially set to a medium value, equal to coal power plants. In contrast to the area of the other power plant types, this can change during the model. Because windmills cannot be put close to each other, the availability of space is determined by the amount of wind farms that are currently installed.

### **The processes of power plants: definitions of their operational configurations**

The processes of power plants are discussed in this section. They result in a definition of their input-output structure. The inputs and outputs of power plants are flows. The amounts of the flows are represented in operational configuration. Each input and output is represented in one operational tuple, describing the name of the commodity, the amount, the unit attached and a set of labels describing this input or output. Together all inputs and outputs form an operational configuration. Such a configuration is made for all power plants to represent their operation. The processes of power plants as well as data and calculations for their operational configurations are presented per power plant type. The power plants are assumed to have an efficiency of 45%. A summary of the outcomes is presented in Table 17.

**Table 17. Operational configurations of power plants.**

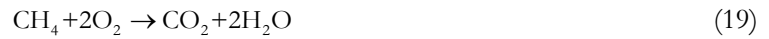
<i>plant type</i>	<i>input good</i>	<i>amount</i>	<i>unit</i>	<i>output good</i>	<i>amount</i>	<i>unit</i>
nuclear	uranium	2.00 x 10 <sup>5</sup>	ton	electricity	1.00	MWh
CCGT	natural gas	222	m <sup>3</sup>	electricity	1.00	MWh
	air	2.12 x 10 <sup>3</sup>	m <sup>3</sup>	water vapour	444	m <sup>3</sup>
				heat	1.22	MWh
				exhaust	1.70 x 10 <sup>3</sup>	m <sup>3</sup>
				CO <sub>2</sub>	0.437	ton
CFSTP	coal	0.276	ton	electricity	1.00	MWh
	air	2.93 x 10 <sup>3</sup>	m <sup>3</sup>	water vapour	238	m <sup>3</sup>
				heat	1.22	MWh
				exhaust	2.25 x 10 <sup>3</sup>	m <sup>3</sup>
				CO <sub>2</sub>	0.934	ton
wind	wind	1.00	MWh	electricity	1.00	MWh
clean coal	coal	0.276	ton	electricity	1.00	MWh
	air	2.93 x 10 <sup>3</sup>	m <sup>3</sup>	water vapour	238	m <sup>3</sup>
				heat	1.22	MWh
				exhaust	2.25 x 10 <sup>3</sup>	m <sup>3</sup>
				CO <sub>2</sub>	0.00*	ton
biomass	biofuel	0.276	ton	electricity	1.00	MWh
	air	2.83 x 10 <sup>3</sup>	m <sup>3</sup>	water vapour	238	m <sup>3</sup>
				CO <sub>2</sub>	0.00*	ton

### *Nuclear power plant*

In a nuclear power plant, subatomic particles are shot at uranium bars. This process, splits up the uranium atoms in smaller atoms and mass of electrons is converted to energy. One kg of uranium can produce 50 MWh of electricity (DYG 2003).

### *Combined Cycle Gas Turbine*

A combined cycle gas turbine (CCGT) uses natural gas as fuel that it burns. The heat is transferred to water to produce steam. Thermal energy is through a steam turbine converted to mechanical energy. This turbine produces electricity by converting this rotating energy to electricity. The overall chemical reaction of a CCGT:



The electric efficiency of a CCGT in The Netherlands is particularly 45%. Binas (Verkerk *et al.* 1998) reports that the lower heating value of natural gas is 36 MJ/m<sup>3</sup>. In addition, the molar volume of a standard gas is 0.0224 m<sup>3</sup>/mol. Finally, the molar weight of CO<sub>2</sub> is 44 g/mol and the amount of oxygen in air is 21 volume percent.

An input output scheme is calculated using Excel. Input flows are natural gas and air. Output flows are electricity, CO<sub>2</sub>, heat and water vapour. Based on the figures above calculations are made of the input-output flows relative to the amount of electricity produced. The amounts of natural gas, CO<sub>2</sub>, heat and water vapour are calculated with the following formulas. The outcomes are summed up in Table 17.

$$\begin{aligned} \text{gas [m}^3\text{]} &= \frac{\text{electricity [MWh]} \times \text{electric efficiency [-]}}{\text{lower heating value gas [MJ/m}^3\text{]} \times 3600 [\text{MWh/MJ}]} \\ \text{air [m}^3\text{]} &= \text{gas [m}^3\text{]} \times 2 [\text{mol air/mol gas}] \times \text{volume fraction oxygen in air [-]} \\ \text{CO}_2 [\text{ton}] &= \frac{\text{gas [m}^3\text{]} \times \text{molair mass [g/mol]}}{\text{molar volume [m}^3\text{/mol]} \times 10^6 [\text{g/ton}]} \\ \text{water vapour [m}^3\text{]} &= \text{gas [m}^3\text{]} \times 2 [\text{mol water vapour/mol gas}] \\ \text{heat [MWh]} &= \text{electricity [MWh]} \times \frac{1 - \text{electric efficiency [-]}}{\text{electric efficiency [-]}} \end{aligned} \quad (20)$$

### *Coal fired steam power plant*

A coal fired steam power plant (CFSP) burns coal as fuel. The heat is transferred to water in order to produce steam. Thermal energy is by a steam turbine converted to mechanical energy. This turbine produces electricity by converting this rotating energy to electricity. The overall chemical reaction of a CFSP is:



The electric efficiency of a CCGT in The Netherlands is particularly 45%. Binas (Verkerk *et al.* 1998) reports that the combustion value of coal is 29 MJ/kg. Furthermore, the molar volume of a standard gas is 0.0224 m<sup>3</sup>/mol. In addition, the molar weight of CO<sub>2</sub> is 44 g/mol. Finally, the amount of oxygen in air is 21 volume percent.

An input output scheme is calculated using Excel. Input flows are coal and air. Output flows are electricity, CO<sub>2</sub>, heat and water vapour. Based on the figures above calculations are made relative to the amount of electricity produced. The amounts coal, CO<sub>2</sub>, heat and water vapour are calculated with the following formulas. The outcomes are found in Table 17.



$$\begin{aligned}
\text{coal [ton]} &= \frac{\text{electricity [MWh]} \times \text{electric efficiency [-]} \times 10^3 \text{ [kg/ton]}}{\text{combustion value coal [MJ/kg]} \times 3600 \text{ [MWh/MJ]}} \\
\text{air [m}^3\text{]} &= \frac{\text{coal [ton]} \times 1.25 \text{ [mol air/mol coal]} \times \text{vol. frac. oxygen in air [-]} \times \text{molar volume [m}^3\text{/mol]}}{10^6 \text{ [g/ton]} \times \text{molair weight CH [g/mol]}} \\
\text{CO}_2\text{[ton]} &= \text{coal [ton]} \times \frac{\text{molair mass CO}_2 \text{ [g/mol]}}{\text{molair mass coal [g/mol]}} \\
\text{water vapour [m}^3\text{]} &= \frac{\text{coal [ton]} \times 0.5 \text{ [mol water vapour/mol coal]} \times \text{molar volume [m}^3\text{/mol]}}{10^6 \text{ [g/ton]} \times \text{molair weight CH [g/mol]}} \\
\text{heat [MWh]} &= \text{electricity [MWh]} \times \frac{1 - \text{electric efficiency [-]}}{\text{electric efficiency [-]}}
\end{aligned} \tag{22}$$

### *Wind farm*

A wind farm converts wind energy to electrical energy. The first conversion is from kinetic energy in the wind to mechanical rotation energy in the rotor. Subsequently, the rotation energy is converted to electricity. There is no fuel consumption, so no calculations have to be made.

### *Clean coal power plant*

A clean coal power plant uses coal to produce electricity, similar to a CFSP. However, the CO<sub>2</sub> stream, an output of this process, flows in a (empty) gas field. As a consequence, the CO<sub>2</sub> emission is zero.

### *Biomass power plant*

A biomass power plant converts bio-fuel, several substances of plants or trees, to electricity by combustion. The calculations are similar as the ones of coal, since bio-fuel has the same chemical composition as coal. In contrast to coal power plants, the CO<sub>2</sub> emissions do not count as such, because they are renewable. The main argument is that the emitted CO<sub>2</sub> was recently removed from the same atmosphere during the life of the plants and trees.

## Appendix C. Scenario data trends

This appendix contains a presentation and discussion of the data used to describe the scenarios. An overview of all data and trends is redrawn in Table 18.

**Table 18. Scenario data values and trends.**

<i>driving forces</i>	<i>factors influenced</i>	<i>initial value</i>	<i>high trend</i>	<i>medium trend</i>	<i>low trend</i>
world economy	aggregate electricity demand	106 TWh	+ 4%/year	+ 2%/year	+ 0%/year
growth	average margins in supply bids	constant	15%	10%	5%
	CO <sub>2</sub> right demand of other industry	constant	10 Mton	5 Mton	0 Mton
	natural gas price	0.144 €/m <sup>3</sup>	+ 6%/year	+ 4%/year	+ 2%/year
	coal price	52.6 €/ton	+ 3%/year	+ 2%/year	+ 1%/year
	uranium price	40 €/kg	+ 5%/year	+ 3%/year	+ 1%/year
	bio-fuel price	66 €/ton	+ 2%/year	+ 1%/year	+ 0%/year
environment	amount of JI/CDM allowances bought	constant	10 Mton/year	5 Mton/year	0 Mton/year
mindedness	technology specific subsidies	constant	100 €/MW	50 €/MW	0 €/MW
external	cap width	50 Mton	- 2%/year	- 1%/year	+ 0%/year
limitations	part of rights grandfathered	constant	70%	80%	90%
	electricity import price	15 €/MWh	+ 2%/year	+ 1%/year	+ 0%/year
	inter-connector capacity	20 TWh	+ 0%/year	+ 1%/year	+ 2%/year
	types of power plants available	constant	no clean coal	clean coal	clean coal

The three driving forces that are the axes of the scenario space can be varied. Because all scenarios are extremes, high and low values are needed. To be able to run scenario zero, data are included for average trends. In chapter four, the influenced factors have been discussed. In this appendix, the values and trends are per driving force discussed. All trends are in the model somewhat unpredictable by multiplying the change with a small normal distribution.

### World economy growth

- The initial value for the aggregate electricity demand, 106 TWh, is the Dutch total electricity consumption of 2004 (EnergieNed 2006). The growth trend of the total demand has been 2% average in the past decades, and that is therefore the medium trend. More than 4% growth per year never occurred. Therefore, 4% is extreme growth. Decreasing demand is very unlikely. Low economic growth therefore implies no growth in demand for electricity.
- The average profit margins of companies are assumed to be constant during a simulation run. The actual levels differ per agent and are part of their management style and market position. However, the economic growth has influence to the margin that can be added to bids on the market. Under high economic growth, it is assumed that 15% margin is possible. In contrast, under medium economic growth this is 10%. Under low economic growth this is 5%.
- The demand for CO<sub>2</sub> rights of the industry beyond their cap makes the market for CO<sub>2</sub> rights tighter. External demand on the market is assumed constant, varying between 0 and 10 Mton of rights.
- The prices for fuels all start at recent price levels. For natural gas used in industry in The Netherlands in 2004 the value is 0.144 €/m<sup>3</sup> (CBS 2006; EnergieNed 2006). A growth of 6% in this price per year is expected during large economics growth. This growth is caused by fast depletion of domestic resources for natural gas. Scarcity leads to high prices. Medium economic growth is expected to result in 4% rise in price, because prices for gas have been rising for the past 5 years, because of scarcity of the resources at the current use levels. Low economic growth is assumed to result a rise of gas price of 2%.
- The average coal price in the Netherlands in 2004 is 52.6 €/ton (CBS 2006). Prices for coal were relatively low the last years, because the use of coal was made unattractive by many governments. Now more advanced, more environmentally friendly technologies come available this attitude is changing. Therefore, the use of coal is generally expected to increase and the assumption is made that prices for coal will increase. However, coal reserves are very large. Therefore, the price increase will be modest. The amount of increase is assumed to vary from 1-3%/year, depending on the economic growth.

- Prices for uranium are low, because the electricity output is very great per use of uranium. Uranium prices are around 65 €/kg (Stichting PeakOil-Nederland 2006). Because many power plants are momentarily built in the world, and the resources for uranium are far more limited than coal, it is assumed that prices for uranium will rise reasonably fast, 1-5%/year, depending on the economic growth.
- The market for bio-fuels is quite new. Biomass is only recently been produced for use in power plants. Different biological products can be used to be burned in power plants. For those reasons, it is assumed that the market for bio-fuels will grow and prices will not rise. Currently, prices for bio-fuels are within large ranges, the average value of 66 €/ton is used (Department for Transport 2006). Prices are assumed to decline 0-2%/year, depending on the economic growth, where more economic growth means less price declination.

### Environment mindedness

- The amount of JI/CDM allowances bought by government to increase the supply side of the CO<sub>2</sub> market is assumed to be a constant amount, in the range of 0-10 Mton/year. The (initial) domestic cap increases 0-20% because of this policy.
- Technology specific subsidies can be used by the government in order to increase the attractiveness of environmentally friendly power plants. Subsidies are 0-100 €/MW capacity, depending on the value for the driving factor environment mindedness. Because the investment costs of environmentally friendly power plants are in the order of 1150-2000 €/MW capacity, the subsidy is 0-8% of the total investment costs.

### External limitations

- The CO<sub>2</sub> cap width is, in the first period (2005-2007) set to 50 Mton for the electricity sector (Cozijnsen *et al.* 2005). On the very long term, the government has as goal to reduce CO<sub>2</sub> emissions far below the amounts in the Kyoto agreement. Consequently, the cap for CO<sub>2</sub> rights has to decline. Depending on the trend of external limitations, the declination is assumed 0-2%/year.
- The parts of the grandfathered rights are regulated to be at least 95% in the first trading period (2005-2007). In the second period (2008-2012) this will be at least 90%. Because this figure is very uncertain, a wide range of constant values is chosen: 70-90% of the rights are grandfathered, based on the external limitations.
- The electricity import capacity used was in 2003 in The Netherlands 20.8 TWh and prices are known to be lower than domestic market prices (Energie in Nederland 2006). It is expected that the costst for foreign electricity generation will increase in the future, because of the drive towards sustainability and rising fuel costs. Therefore, increase in import prices are assumed to occur within the range of 0-2%/year, depending on the amount of external limitations.
- Inter-connector capacity can increase in the future, but will remain limited because of the high costs involved. Additionally, huge extension is unacceptable for reasons of dependence on electricity delivery by other countries. Furthermore, transport losses over long distances are significant. Increase in import capacity is assumed to be within a range of 0-2%/year, where more stringent external limitations mean lower increase in import capacity.
- The types of technology for electricity production in the Netherlands are in the model. The only exception is the innovative clean coal concept. Under stringent limitations, CO<sub>2</sub> storage in (empty) gas fields will not be developed.

## Appendix D. Management styles and market positions of electricity producers

This appendix contains a presentation of the parameters that describe the management styles and market positions of the electricity producers. The values used are given in Table 19. A management style and market position is presented for six electricity producers. The values are chosen to reach widest range of realistic management styles and market positions. Within the limitedness of only six players, not all possible combinations can be set. Consequently, no full factorial analysis is made. This choice was made, because it is not expected that the electricity market will exist of more than six players. Note that in the model, random management styles and market positions can be selected as well.

**Table 19. Parameter values of the management styles and market positions of electricity producers.**

<i>management style and market position parameter of electricity producer</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>	<i>6</i>
margins in supply bids (% of average margin)	125	125	100	100	75	75
maximum years of losses before disinvestment	5	9	7	9	5	7
maximum concurrent investments	10	8	6	10	8	6
demand/supply ratio barrier for investing	0.70	0.83	0.95	0.83	0.70	0.95
economics factor	5	5	5	3	3	3
environmentally friendliness factor	0	1	2	0	1	2
conservativeness factor	1	2	1	2	1	2
nuclear fear factor	4	4	2	2	4	4

The values of the three four factors are selected such, that the widest range of combinations is covered that is possible within the limitations of six players.

- The first factor determines what margin is included in bids on the electricity market. The average profit margin of all producers is determined by the scenario and is a indicator for strategic behaviour. The margin bids vary between 75 and 125% of the average margin.
- An electricity producer can disinvest current generation capacity because power plants are not profitable enough. The maximum years of concurrent losses before disinvestment occurs varies between 5 and 9 years.
- There is a maximum to the concurrent investments of an electricity producer. This maximum ranges between 6 and 10.
- The ratio demand/supply is an indicator for the risk a producer is willing to take. When the demand of electricity comes closer to the total supply capacity, there is room for expansion of the electricity portfolio and electricity producers invest in new capacity. The barrier ranges between 70 and 95% of supply capacity in use by demand.

The last four factors are weight factors in the multi-criteria analysis in which a choice is made between different alternative power plants. See chapter five for details on that analysis. The values of these four last factors are selected such, that the widest range of combinations is covered possible.

- The profitability of power plants is the often the dominant criterion for companies, because they are in a liberalized market and the main goal of the company is to make a profit. Two values are used: a high value of 5 and low value of 3. Both values are high relative to the other weight factors.
- Many electricity producers claim to be environmentally friendly. Therefore, the environmentally friendliness of power plants are taken into account. This criterion has lower values than for the profitability. The values are 1 and 3. As a consequence, it is never of higher importance than the profitability.
- The factor for conservativeness of producers differ, because some are assumed to take fewer risks in investing in technologies that are new or different than currently installed. This effect is not dominant, and therefore ranges between 1 and 2.
- The final factor is the nuclear fear factor. Companies can have strong feelings against the use of nuclear power plants, because it has the image of being very risky. Nuclear fear is also determined by the government. The fear for nuclear is taken at high levels, namely 2 and 4, because nuclear fear in the Netherlands is high.

## Appendix E. Validation of the electricity market model

In this appendix, the electricity market model is validated by comparisons with historic data. Recall that the main formulas in the model are:

$$\text{supply of installation} = \text{capacity installation} \times \frac{\text{total demand}}{\text{total supply capacity}} \times \frac{\text{average capacity weighed bid}}{\text{bidding price installation}} \quad (23)$$

$$\text{price for installation} = 40 \times \frac{\text{total demand}}{\text{total supply capacity}} \times \frac{\text{bidding price installation}}{\text{average capacity weighed bid}} \quad (24)$$

Under the realistic assumption that 20% reserve capacity is installed, total demand over total supply capacity is 0.8. The boundary between base and peak load is the installation for which holds that the actual supply equals the capacity (see Figure 23). This means that:

$$\frac{\text{total demand}}{\text{total supply capacity}} \times \frac{\text{average capacity weighed bid}}{\text{bidding price installation}} = 1 \quad (25)$$

As a consequence, the formula can be simplified to:

$$\text{bidding price installation} = 0.8 \times \text{average capacity weighed bid} \quad (26)$$

Consequently, the bidding price for the installation that is on the boundary between base and peak load has a bid price of 80% of the average capacity weighed bid. Because of the definition of the average capacity weighed supply bid, this means, that 40% of the capacity is part of base load. That coincides with the load duration curve of the Dutch electricity generation portfolio (based on TenneT data).

The price paid for the electricity produced by that installation would be:

$$\frac{\text{average capacity weighed supply bid}}{\text{bidding price installation}} = 1/0.8 = 1.25 \rightarrow \text{price for installation} = \frac{40 \times 0.8}{1.25} = 25.6 \quad (27)$$

Based on historic data from TenneT (2006) and ECN data, its bid price should than be around 25 €/MWh and is thus valid.

Further more, an installation that runs only during peak demand is validated. Consider an installation with a bidding price 2 times as high the average capacity weighed supply bid. Following the formulas in the used model and under the assumption of 40% reserve capacity, the following running capacity is found:

$$\frac{\text{supply of installation}}{\text{capacity installation}} = 0.6 \times 0.5 = 0.3 \quad (28)$$

This installation in the model runs at 30% capacity. This is a bit higher than in ECN data. Consequently, installations that only run under peak demand in reality would probably run a little less than in the model. The revenue from peak demand is thus overestimated. Therefore, the incentive to disinvest in reality comes earlier than in the model. In the future, more sophisticated formulas can be used to cope with that issue.

## Appendix F. The software tools brought together as a agent-based modelling environment

In this appendix, the process is described in which software tools were coupled in order to develop the agent-based model. Together the software tools form an agent-based modelling environment. The software tools use Java as programming language. I am very grateful to the efforts of Igor Nikolic regarding this coupling process. The main tool is the Eclipse, an integrated development environment. The model code is developed in Eclipse. In addition, it is the central tool to which two other tools connect. The first connection is made through libraries of Protégé to connect with the database that contains the database of agents and technological installations. Second, a connection is made with Repast, the software tool used for running agent-based simulations.

A connection between java programs is made by using libraries. A library is a file format for sets of compiled java programs (e.g. Sun Microsystems 2006a). Java libraries are coupled to Eclipse projects. When coupling a library, the *object types* and their methods, defined in these libraries, are available for use in the project.

### Protégé and Eclipse

Coupling the Protégé structure and database to Eclipse is possible because of the modular structure of the java programming language. The classes and instances in Protégé are essentially not java classes and instances. They are contained in a database of another format. However, communication with the database can take place through java code. To be able to read and use the information of the Protégé database, two converting tools had to be developed. First, a class and properties structure representation in java was developed. Finally, a database reader was developed.

#### *Class and properties structure representation in java*

It was preferred to build the ontology (structure of concepts and properties) in the Protégé software package because of the complexity and iterative setup of the design process. Usability and reusability of working in direct java code is limited and it is not flexible enough. However, no translation packages exist yet that can create a complete java class structure from the ontology in Protégé. Developing such a package is too complex for this project. For now, all classes and their properties were programmed by hand in java code. This translation step started when it was understood that the structure of the ontology was stable.

This translation process was a product of the complete sub group of agent-based modellers that use this environment. All classes in the ontology were defined in java. In addition, all slots of the ontology were translated to java-variables. The slots link to other classes of the ontology. This results in a highly connected network of java classes. The class structure is generic and separated from the models.

#### *Database java reader*

The second conversion tool that had to be made was a java database reader. For reasons of user friendliness and reusability, agents and technological installations are defined in Protégé and stored in its database. This reader converts those entities or instances contained in the Protégé database to (collections of) java objects in agent-based models. For the model of this thesis, the conversion functionality for physical, economic and design properties and case labels of agents and technological installations was developed. Note that the instances defined in Protégé are only objects with values representing characteristics of items in real life. Behaviour is not included in the database and resides in the agent-based models.

### Coupling Eclipse to Repast

The final coupling that has to be made is the one to the simulation package, called Repast. This package is completely written in java and this makes connecting much easier. Only java libraries had to be coupled and specific classes of objects be used. This was all arranged in earlier models. Two of the top classes of the ontology, node and edge were also coupled to specific Repast classes, to make many methods available, such as for displaying.

## Appendix G. Overview of the structure of concepts (ontology)

The system decomposition method for evolutionary analysis of complex systems of (Dam *et al.* 2006) is used to create a formalized description of the concepts used in this thesis as described in chapter four. This formalization process was done in collaboration with members of the Energy and Industry group, through discussions that followed this method. “The goal is to identify the internal structure of a problem space (the system to be observed) in such a manner that the evolutionary analysis of the system becomes possible” (Dam *et al.* 2006). This method is used to present a structured overview of the *process* that actually occurred during the development of the ontology. The three main steps in this method are displayed in Figure 50.

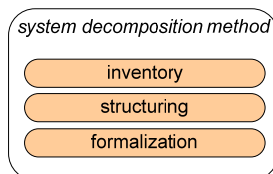


Figure 50. System decomposition method (based on Nikolic *et al.*, 2007).

In the first step, an inventory is made of the problem, the system, the relevant time scale, actors involved, identifiable concepts and objects and interactions between them. Second, the inventory is structured to identify objects. Objects are identifiable things that have boundaries and have properties. These properties can be static or dynamic. All objects are placed in a hierarchy and links between them are identified. Third, the found concepts are formalized. Formalized concepts have an unambiguously clear meaning. As a consequence, messages about formalized concepts are machine-readable and understandable. A set of formalized concepts and their relations is called an ontology. Noy (2006): “An ontology is a formal explicit description of concepts in a domain of discourse (classes, sometimes called concepts), properties of each concept describing various features and attributes of the concept (slots, sometimes called roles or properties), and restrictions on slots (facets, sometimes called role restrictions).”

The main concepts are discussed and the complete class hierarchy is displayed (see Figure 52). The four main branches are node, edge, knowledge and data. Nodes are points in a network, such as agents and technological installations. Edges are possible connections between nodes, such as contracts and flows. Data are a structured set of possible properties of nodes and edges. Knowledge contains data on the operation of technological installations.

The ontology contains classes and slots. A *class* of objects is a collection of objects of the same type. A *concept* represents such a class of objects. By collaborative work within the Energy and Industry Group, they were hierarchy organized. More details on this collaboration process can be found later this appendix. All agents, such as electricity producers and governments, belong to the same class, called Agent. An additional example is displayed in Figure 51, where is shown that *physicalFlow* and *dataFlow* are subclasses of *flow*. That is also observed in Figure 52 under the branch edge. This means, that each physical and data flow are flows; a flow could be data flow, a physical flow or another type of flow.

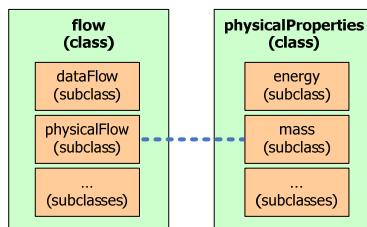


Figure 51. Objects in classes and their relations.

Each type (class) of objects may have several properties or characteristics. In Protégé, all characteristics are called *slots*. A slot contains a name and a reference to an object of some class in the hierarchy. A physical flow has a slot called *physicalProperty*, namely an object of the type *physicalProperty* or a subclass

of *physicalProperty* that says something on a physical property of that physical flow. In other words, the mass of a physical flow refers to the object of the class *mass*, a subclass of *physicalProperty*. The mass class can be found in one of the lower hierarchical layers in the data branch. Consequently, slots are cross connections between different sections the ontology.

The hierarchical network is also relevant for slots. That is because of the inheritance of properties: A lower-level class inherits the properties of a higher-level class. For instance, the node class has a label slot. Because of inheritance, all subclasses of node, such as agent, also have this property. In addition, lower-level classes can extend the set of properties or specify properties further. For instance, all physical properties have a property that contains its actual value. The property mass has a more specific value, namely that it must be numeric. Slots may be ‘required’; they need to have a value. Coding the use of those slots is less laborious, because it is a priori known that a value will be returned.

The development of the ontology started before this thesis project. It is built by a collaboration process of members of the Energy and Industry Group. The ontology is used for several agent-based models of this group. A preliminary version existed when I joined Koen van Dam, Igor Nikolic and Michiel Houwing in its development. The ontology was further developed during discussions. Developing the ontology is an ongoing process towards a more robust generic description of concepts in which an increasing variety of models can be fit. The choices were trade-offs between the following criteria:

- formal correctness
- conceptual correctness
- practical use

The development was very iterative, because of all interdependencies in the ontology. It is a product of all participants in the discussions, but specific suggestions were needed for the model of this thesis. The focus of this section is therefore on those issues. First, the formally correct use of physical flows and the full separation of agents and technological installations was needed in order to apply the three-layer model, presented in chapter three. Second, the trade of CO<sub>2</sub> rights was impossible because only physical commodities were tradable. The discussion is ongoing, how to incorporate intangible goods. For this model, a temporary solution was developed. Third, the progress in the development of the ontology was essential because the scope of an MSc thesis project is smaller than that of the PhD researches of the other contributors.

The ontology is larger than strictly needed for this research and is functional for multiple agent-based models. As a consequence, only a selection of this ontology is used in my model. In addition, communication and integration with (parts of) other models is possible.

The development of the ontology is a creative process, because the discussions encourage contributors to think in other domains and reflect on own research. Participants have to switch between different levels of abstraction and different domains, in order to realize the consequences of choices. Since new barriers emerge during the model development process, development of the ontology will continue.



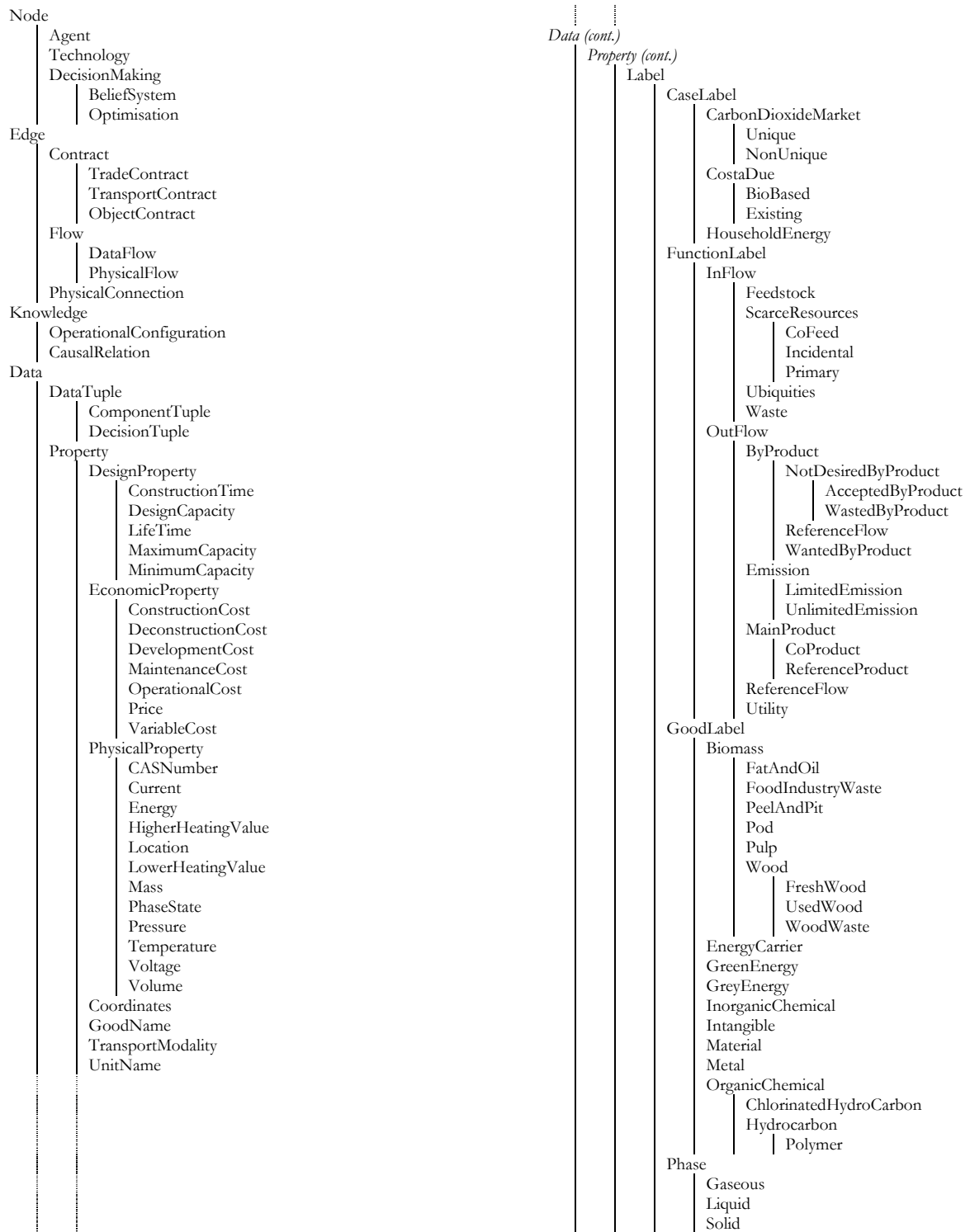


Figure 52. Class hierarchy in ontology.

## Appendix H. Sensitivity analysis

This appendix presents the sensitivity analysis that was performed to validate the model. The goal of this analysis is to give insight in the sensitivity of the model to its input parameters. The procedure and outcomes are described in this appendix, but the conclusions can be found in chapter six.

All input parameters are varied 10% above and below the value. By varying 10%, the variation of the output is measured. A change in the output of more than 10% means that it is a sensitive parameter, less than 10% means a non-sensitive parameter. The chosen output parameters are general indicators of system behaviour of the model. For practical reasons, it is important to take only a few of output parameters. The first parameter is the average market volume of rights on the CO<sub>2</sub> market in ton/year. That is one of the main CET indicators. The second parameter is the average electricity price, one of the main indicators in the electricity market.

**Table 20. Overall output parameters.**

	<i>average CO<sub>2</sub> market volume</i>	<i>average electricity price</i>
average	5.12 Mton	21.24 €/MWh
standard deviation	0.09	1.23
standard deviation relative	1.79%	5.77%

The model is run to find the average output without the change of any input parameters. Because of the stochastic elements in the model, the output of simulation runs varies even with equal input settings. Therefore, the average value and the standard deviation of 20 runs are calculated. Note that all runs in the sensitivity analysis are under scenario zero. The outcome of those 20 runs are presented in Table 20. The average market volume of CO<sub>2</sub> rights on the market is 5.12 Mton and the standard deviation is only 1.79% of that figure. The outcome is by definition with 96% probability within two times the standard deviation. That means that 96% of the runs will have a deviation of less than  $2 \times 1.79\% = 3.6\%$ , and for values of  $5.12 \pm 3.6\%$  no deviation can be measured. As a consequence, measuring high sensitivity starts beyond 10% deviation. The average electricity price is 21.24 €/MWh and the standard deviation is 5.79% of that figure. For this parameter, that means that 96% of the runs will have a deviation of less than  $2 \times 5.79\% = 11.5\%$ , and for values of  $21.24 \pm 11.5\%$  no deviation can be measured. A 10% change in the output is therefore not an indicator for any sensitivity. Therefore, only high deviation values, such as 20% are indicators of high sensitivity.

All input parameters are used in this analysis. The scenario input data and the trends are included. The management style and market position parameters used to describe the electricity producers are used and all properties of power plant types. An overview of the parameters and the sensitivity output of model runs is presented in Table 21. Relative large percentages are red, small positive are green and small negative are brown.

**Table 21. Outcomes sensitivity analysis.**

<i>input parameter</i>	<i>base value</i>	<i>base value -10%</i>				<i>base value +10%</i>			
		avg. CO <sub>2</sub> volume	avg E-price	avg. CO <sub>2</sub> volume	avg E-price	avg. CO <sub>2</sub> volume	avg E-price	avg. CO <sub>2</sub> volume	avg E-price
		Mton	rel. %	€/MWh	rel. %	Mton	rel. %	€/MWh	rel. %
<b>scenario input parameters</b>									
initial reserve capacity electricity	20%	5.17	1.06%	21.59	1.67%	5.05	-1.34%	21.89	3.06%
aggregate electricity demand	106 TWh	5.00	-2.28%	22.92	7.93%	5.40	5.58%	21.09	-0.70%
average profit margins of companies	10%	5.23	2.23%	21.16	-0.35%	5.08	-0.78%	21.00	-1.12%
carbon dioxide right of industry	5 Mton	4.57	-10.63%	22.01	3.66%	5.58	8.99%	26.36	24.15%
natural gas price	0.144 €/m <sup>3</sup>	5.10	-0.23%	22.57	6.27%	5.08	-0.71%	21.35	0.54%
coal price	52.6 €/ton	5.27	2.91%	22.12	4.15%	5.35	4.51%	24.76	16.60%
uranium price	40 €/kg	5.22	2.03%	22.14	4.25%	5.07	-0.93%	23.41	10.23%
biofuel price	66 €/ton	5.19	1.40%	22.36	5.31%	5.11	-0.08%	21.31	0.34%
JI/CDM allowances bought	1 Mton	5.13	0.28%	23.27	9.59%	5.12	0.08%	22.08	3.96%
technology specific subsidies	50 €/MWh	5.02	-1.86%	21.14	-0.47%	5.03	-1.62%	22.67	6.76%
cap width	50 Mton	5.54	8.21%	22.75	7.13%	5.05	-1.29%	19.76	-6.94%
part of rights grandfathered	80%	5.86	14.46%	22.30	5.02%	5.00	-2.28%	21.24	0.04%
electricity import price	15 €/MWh	5.09	-0.60%	20.48	-3.55%	5.09	-0.48%	22.46	5.76%
electricity import capacity	20 TWh	5.12	0.08%	23.09	8.75%	5.38	5.20%	22.15	4.32%
spatial limitation	10	5.13	0.30%	22.34	5.18%	5.10	-0.41%	20.80	-2.05%
government nuclear fear	100	5.25	2.55%	21.39	0.74%	5.03	-1.63%	22.81	7.40%

<i>input parameter</i>	<i>base value</i>	<i>base value -10%</i>				<i>base value +10%</i>			
		avg. CO <sub>2</sub> volume		avg E-price		avg. CO <sub>2</sub> volume		avg E-price	
		Mton	rel. %	€/MWh	rel. %	Mton	rel. %	€/MWh	rel. %
<b><i>scenario trends</i></b>									
aggregate electricity demand	+2%/year	5.36	4.76%	24.16	13.77%	5.15	0.59%	20.95	-1.32%
price electricity import	+1%/year	5.24	2.40%	21.93	3.27%	5.22	1.94%	25.78	21.38%
capacity electricity import	+1%/year	5.11	-0.09%	23.30	9.71%	5.16	0.85%	21.30	0.29%
domestic cap CO <sub>2</sub>	-1%/year	5.00	-2.28%	22.42	5.58%	5.14	0.50%	22.79	7.33%
price gas	+0%/year	5.25	2.51%	22.82	7.45%	5.19	1.36%	23.04	8.47%
price coal	+2%/year	5.25	2.61%	21.31	0.36%	5.02	-1.80%	24.42	14.99%
price uranium	+3%/year	5.03	-1.60%	24.24	14.15%	5.12	0.10%	20.82	-1.96%
price bio-fuel	+1%/year	5.06	-1.02%	20.47	-3.59%	5.05	-1.25%	24.12	13.56%
<b><i>management style and market position parameters</i></b>									
margin in supply bid	75-125%	5.23	2.23%	21.16	-0.35%	5.08	-0.78%	21.00	-1.12%
maximum concurrent investments	6-10	5.20	1.69%	22.56	6.24%	5.08	-0.62%	22.09	4.02%
demand/supply barrier for investing	0.70-0.95	5.11	-0.20%	22.90	7.84%	5.29	3.41%	23.31	9.75%
economics factor	3-5	5.13	0.30%	22.06	3.90%	5.08	-0.76%	21.83	2.78%
environmentally friendliness factor	0-2	5.16	0.92%	25.64	20.75%	5.53	8.16%	22.18	4.43%
conservativeness factor	1-2	5.10	-0.36%	21.43	0.92%	5.02	-1.88%	21.58	1.63%
nuclear fear factor	2-4	5.25	2.55%	21.39	0.74%	5.03	-1.63%	22.81	7.40%
<b><i>power plant characteristics</i></b>									
<b><i>nuclear power plant</i></b>									
lifetime	40 year	5.14	0.38%	24.05	13.23%	5.07	-0.84%	22.65	6.65%
maximum capacity	550-2000 MW	5.08	-0.75%	20.63	-2.86%	5.07	-0.86%	24.29	14.40%
construction time	3 year	5.26	2.74%	23.30	9.71%	5.06	-1.15%	22.03	3.72%
construction costs	2000 €/kW	5.12	0.06%	21.07	-0.78%	5.05	-1.34%	23.85	12.33%
operational costs	10 €/MWh	5.13	0.36%	21.99	3.54%	5.08	-0.67%	21.87	2.97%
area	150 m <sup>2</sup>	5.11	-0.19%	21.76	2.49%	5.13	0.25%	20.44	-3.77%
<b><i>combined cycle gas power plant</i></b>									
lifetime	30 year	5.13	0.20%	21.40	0.79%	5.08	-0.65%	21.44	0.94%
maximum capacity	1000-2250 MW	5.12	0.10%	22.79	7.33%	5.24	2.37%	23.28	9.62%
construction time	3 year	5.08	-0.71%	21.73	2.31%	5.38	5.16%	21.55	1.50%
construction costs	500 €/kW	5.26	2.79%	22.81	7.39%	5.08	-0.71%	22.13	4.19%
operational costs	2 €/MWh	5.38	5.16%	21.60	1.70%	5.09	-0.45%	21.90	3.11%
area	70 m <sup>2</sup>	5.00	-2.28%	21.31	0.35%	5.10	-0.38%	22.79	7.31%
<b><i>coal fired steam power plant</i></b>									
lifetime	30 year	5.10	-0.23%	20.92	-1.50%	5.22	2.07%	21.18	-0.26%
maximum capacity	1000-2000 MW	5.11	-0.06%	22.93	7.98%	5.05	-1.34%	23.84	12.27%
construction time	3 year	5.13	0.24%	21.78	2.54%	5.18	1.22%	21.86	2.94%
construction costs	1250 €/kW	5.22	2.05%	21.36	0.61%	5.10	-0.30%	22.47	5.79%
operational costs	5 €/MWh	5.03	-1.63%	22.70	6.90%	5.20	1.56%	22.79	7.33%
area	100 m <sup>2</sup>	5.10	-0.41%	20.23	-4.73%	5.02	-1.85%	21.01	-1.06%
<b><i>wind farm</i></b>									
lifetime	20 year	5.21	1.92%	21.36	0.57%	5.24	2.51%	22.70	6.89%
maximum capacity	100-2250 MW	5.17	0.96%	20.52	-3.39%	5.08	-0.77%	24.86	17.06%
construction time	3 year	5.12	-0.01%	22.99	8.27%	5.04	-1.54%	22.90	7.81%
construction costs	1150*2 €/kW	5.21	1.87%	19.44	-8.47%	5.13	0.20%	23.78	11.96%
operational costs	10 €/MWh	5.06	-1.13%	21.95	3.38%	5.15	0.60%	22.67	6.77%
area	100 m <sup>2</sup>	5.10	-0.41%	22.57	6.29%	5.09	-0.55%	23.22	9.32%
<b><i>clean coal power plant</i></b>									
lifetime	30 year	5.41	5.75%	21.43	0.89%	5.13	0.34%	22.58	6.34%
maximum capacity	1000-2000 MW	5.39	5.35%	22.47	5.81%	5.17	0.98%	22.68	6.79%
construction time	3 year	5.09	-0.56%	22.29	4.94%	5.13	0.23%	22.05	3.83%
construction costs	2000 €/kW	5.22	2.03%	21.39	0.72%	5.05	-1.21%	23.61	11.20%
operational costs	30 €/MWh	5.12	0.03%	21.15	-0.39%	5.09	-0.52%	24.14	13.69%
area	200 m <sup>2</sup>	5.14	0.40%	22.51	6.01%	5.15	0.66%	24.28	14.36%
<b><i>biomass power plant</i></b>									
lifetime	30 year	5.03	-1.59%	22.23	4.66%	5.04	-1.58%	21.43	0.93%
maximum capacity	100-225 MW	5.12	0.13%	22.04	3.80%	5.07	-0.87%	23.73	11.74%
construction time	3 year	5.16	0.79%	21.80	2.66%	5.05	-1.34%	21.80	2.65%
construction costs	1250 €/kW	5.06	-1.02%	22.22	4.63%	5.09	-0.52%	21.53	1.39%
operational costs	7 €/MWh	5.10	-0.23%	22.26	4.82%	5.09	-0.61%	24.65	16.06%
area	100 m <sup>2</sup>	5.12	0.15%	23.15	9.03%	5.21	1.90%	24.24	14.13%

## Appendix I. Simulation results: overview of portfolio development

In this appendix, the portfolio development during simulation runs is visualized, in order to provide a complete overview of the outcomes. Note that the main conclusions can be found in chapter seven.

In Figure 53, the average developing portfolio is drawn per electricity producer. On top, the drawings are with CET. Below, CET is absent. These are averages over all scenarios.

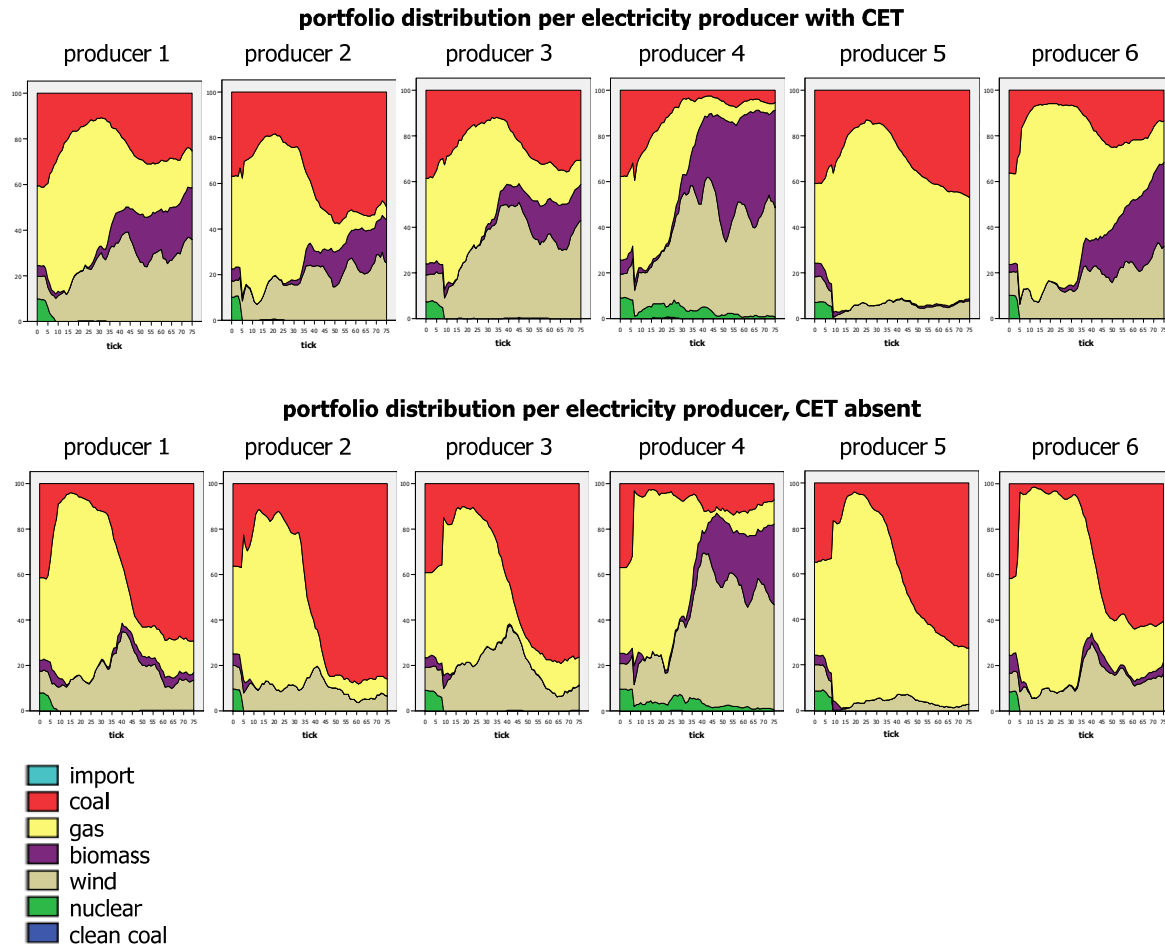


Figure 53. Electricity generation portfolio development per electricity producer.

Finally, developments of the electricity generation portfolio are displayed per scenario. On top, the drawings are with CET. Below, CET is absent.

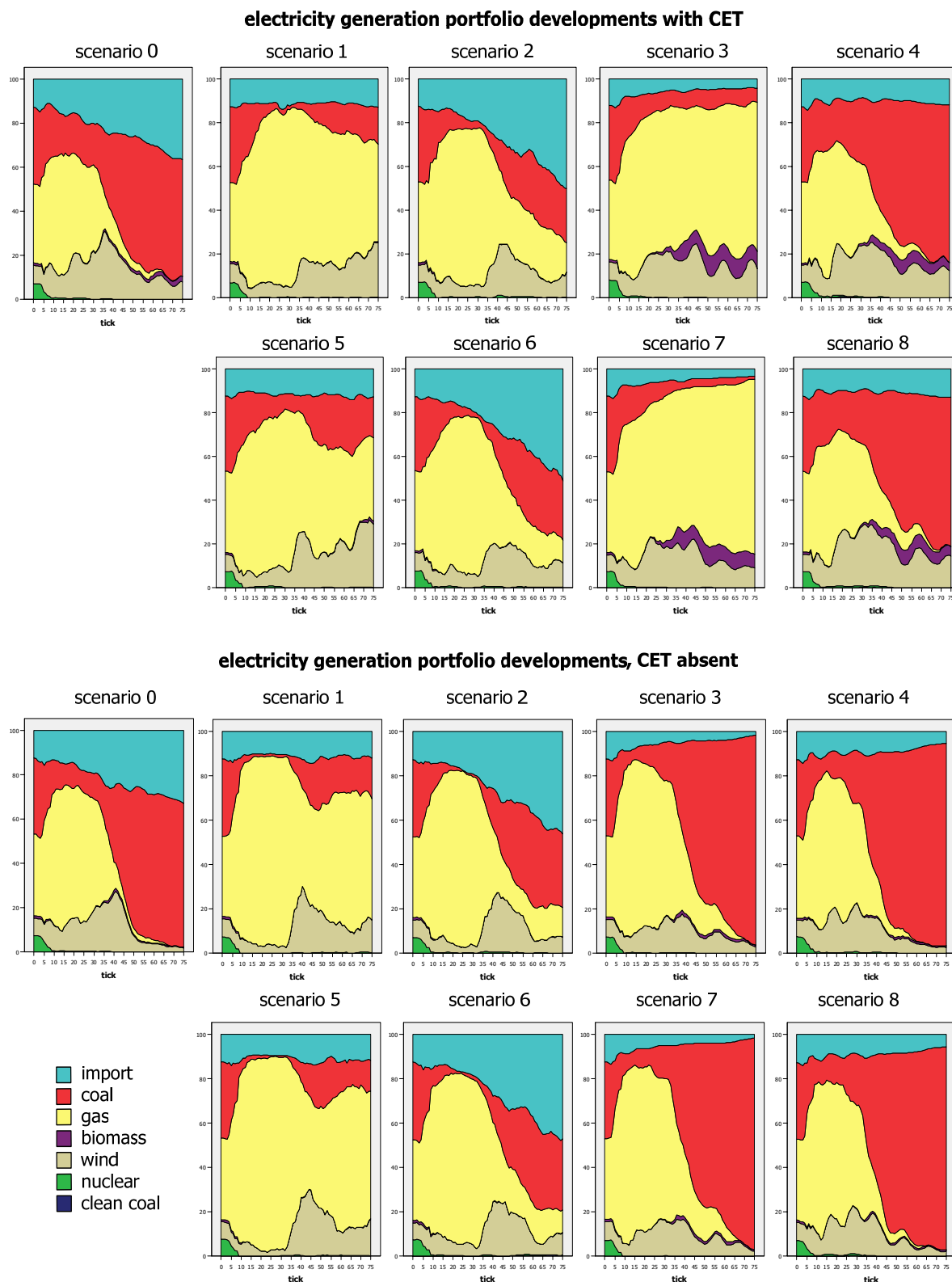


Figure 54. Electricity generation portfolio development under different scenarios.

## **Appendix J. CD-ROM with the model**

Below, a CD-ROM is attached, on which an executable version of the model can be found as well as the source code and its full documentation.

For MS Windows users, the CD-Rom normally starts automatically. If the CD-ROM does not start correctly, press Start, Run and type `X:\index.html`, where *X* stands for the CD-ROM drive. The web-based menu will open in the computers' standard browser.

For Linux users, open the `index.html` file on the root of the CD-ROM in a suitable browser.