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Diplomarbeit

Comparing CO_2 Mitigation Options in the Electricity Sector: Nuclear Power, Renewable Energy and Carbon Sequestration

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20th December 2006

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Acknowledgements

I want to thank everybody who supported my while I was working on this thesis. Especially I would like to mention the following people:

- Ottmar Edenhofer and Thomas Bruckner for supervising this thesis.
- Michael Lueken for exhaustive proof-reading and interesting discussions.
- Charlotte Loreck for hunting those spelling mistakes.
- My friends and my parents for their patience and understanding.

Abstract

The objective of this study was to assess the role of the three main CO_2 mitigation options in the electricity sector. These encompass the transition to carbon free technologies which rely on renewable or nuclear energy sources, and the capture and sequestration of emitted CO_2 (CCS).

To achieve this objective, experiments with a bottom-up model of the electricity sector have been performed. The model is a subset of a comprehensive energy system model that is currently being developed at the *Potsdam Institute for Climate Impact Research* using the modeling toolbox *genEris*. It determines an optimal investment timepath by minizing intertemporally aggregated energy system costs subject to resource and potential constrictions and a cap on emissions. One-factor learning curves are used to endogeneously represent cost reductions due to learning effects.

The model structure has been extended by a complex representation of the nuclear energy sector, including thermal and fast reactors and the main energy and mass conversion steps of the front and back end of the nuclear fuel cycle.

Furthermore, the model has been linked to the multi-run experiment environment *SimEnv*, and sensitivity analysis experiments have been performed to assess the behaviour of the model under different parameter assumptions.

The experiment results show that the model is able to represent a wide range of possible future scenarios. The restriction of emissions accelerates the substition of carbon intensive technologies. The use of CCS is highly sensitive to fossil fuel cost assumptions. The use of thermal nuclear reactors is limited by the restricted resources of uranium. Fast nuclear reactors and photovoltaic compete for the role as a singular backstop technology that dominates the electricity sector after the substitution of fossil energy sources.

The results of this study will be used by further projects with the objective of integrating the energy system model into an integrated assessment tool which includes a macroeconomic growth model, a carbon cycle model and several geographic regions.

1 Introduction

In the near to mid-term future, a fundamental restructuring of the fossil based energy sector will take place. Especially in the electricity sector, during the next decades the expected increase of global electricity demand meets the fact that many power plants reach the end of their lifetime and will need to be replaced. On a larger timescale, the limitation of fossil resources lead to the physical necessity of switching to alternative energy sources.

The transition to an energy system that is not based on fossil fuels is a process that is unavoidable[1] – the important questions are: When will it take place? And how will it look like?

The decisions that will be made will be influenced by the increasing awareness of the issue of climate change. Recent findings indicate that the effects of greenhouse gas emissions are likely to be more severe than it was thought only a few years ago. Due to this change of perception the focus of current research is steadily switching from finding out whether emission reduction are necessary or not to the question how a less carbon intensive future could look like.

This study takes a look at how this question might be answered. A bottom-up cost-minimizing model of the electricity sector was used to evaluate the main CO_2 mitigation options – nuclear power, renewable energy and Carbon Capture and Sequestration. A special focus was set on the implemetatation of the nuclear energy sector which was modeled with a higher degree of detail than it is usually done in models that are used in climate science.

The potential of *thermal* nuclear reactors, the technology that is almost exclusively used today, is limited due to the finite resource base of uranium. Although the scope of this limitation is subject to the same uncertainties as for fossil fuels, it will most likely become a binding constraint during the course of this century.

However, *fast* reactors, if they would be introduced on a large scale, would increase the effiency of uranium use by such a degree that its depletion would not be an issue for the next few hundred years. Critics point out that the potential risks (concerning environmental damages, security and proliferation issues) of such a scenario are so high that it is not even worth to assess its economic feasibility. On the other hand, supporters claim that technological solutions exist to control these problems.

The aim of this study was to investigate the economical value of both options in comparison with others, regardless of the aforementioned external effects. Of course, this does not imply that they are of lesser importance.

Both reactor technologies were integrated into the model, along with a detailed representation of the nuclear fuel cycle in which they are embedded.

[1] Of course, this observation is only true on a large timescale. During the next 100 years, a time horizon which is frequently used in energy system studies, including this one, it is very unlikely that coal resources will become scarce.

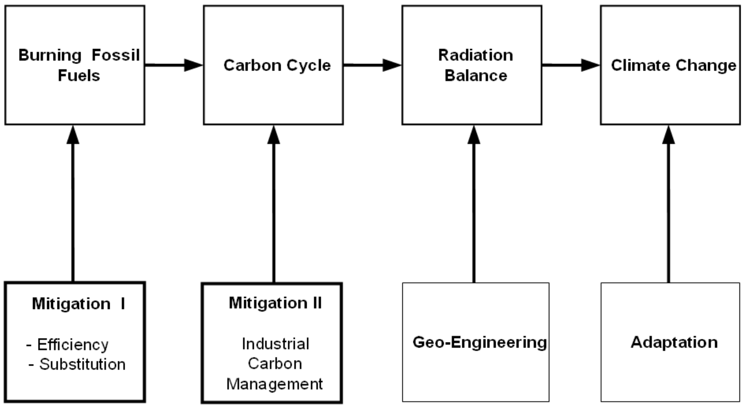

Figure 1.1: What are the steps that lead to climate change, and what options do we have to control it? (Edenhofer, 2006).

The intention was not to find *the* optimal solution, but to explore the different possibilities, to make different assumption about key parameters, and investigate how this affects the choice of CO_2 mitigation options as well as the costs of reducing CO_2 emissions. Therefore a sensitivity analysis of several uncertain parameters has been performed.

1.1 A short introduction to climate change

Figure 1.1 shows the chain of events that lead to climate change. The burning of fossil fuels leads to the emission of greenhouse gases, of which CO_2 is the most relevant one. Emitted CO_2 enters the global carbon cycle where an equilibrium between bioshere, atmosphere and ocean is formed. Eventually, CO_2 emissions lead to a – temporally delayed – increase of atmospheric concentrations. This affects the global radiation balance which results in an increase of the global mean temperature. This increase triggers a variety of climate changes – from gradual changes in weather and precipitation patterns and sea level rise due to the melting of ice caps up to the increased possibility of extreme events like the collapse of oceanic drift patterns.

Figure 1.1 also shows the options we have to control climate change.

- The consumption of fossil fuels can be reduced by two ways: The demand can be reduced increasing the effiency of resource usage, fossil fuels can be substituted by other energy sources.
- If fossil fuels are combusted, part of the CO_2 that is generated can be artificially prevented from entering the Carbon Cycle – which refers to Carbon Capture and Sequestration.
- There are some ideas on how to modify the global radation balance artificially – but these won't be discussed here.
- Once climate change happens, society needs to adapt to the effects.

Of all these option, only those referring to the transition of the electricity sector will be examined in this study. They will be discussed further in the next section.

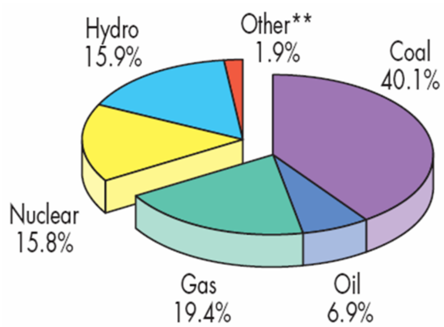

Figure 1.2: Global electricity production in 2003, broken down to different types of energy sources. 67 % of electricity generation was based on fossil resources (IEA, 2005a).

1.2 Mitigation options in the electricity sector

Figure 1.2 shows the global electricity generation mix in 2003. Two third of all eletricity was generated on the base of fossil resources. Half of this share was produced by burning coal, which is the most CO_2 intensive fuel of all. What options are available to reduce emissions in the electricity sector?

- *Fuel switching:* Coal can be replaced by natural gas which is less CO_2 intensive. This will lead to emission reductions, but they will not suffice to achieve ambitious stabilization scenarios, and the resources for gas will most probably be stretched to their limits during this century.

- *Substitution by renewable energy:* Fossil fuels can be substituted by renewable energy sources that do not rely on the combustion of carbohydrates. A broad portfolio of technological options exists, among them wind, solar and geothermal energy, hydropower and the use of biomass as an energy source. However, the share of renewable energy sources needs to be increased substantially to achieve significant reductions, and critics of this option point out that the costs of these technologies are still very high.

- *Substitution by nuclear energy:* Nuclear fission is another energy source that does not produce direct CO_2 emissions. But there are environmental, economical and security-related arguments against the use of nuclear energy, and critics argue that emission reduction would be bought at a high price if this option would be used.

- *Carbon Capture and Sequestration:*[2] This refers to the option of capturing emitted carbon and deposing it in geological or oceanic repositories. It is important to mention that this technology does not reduce the amount of CO_2 that is produced, but it delays – for a certain share of the emissions – the actual release into the atmosphere. The length of this delay depends on the quality of the choosen repositories. Although the potential of this option is limited (due to economic restrictions, the availability of safe repositories and the restriction to large point sources) it is regarded as a possibility to ease the transition to a carbon-free energy system.

[2]In this text, *CCS* will be used as an abbreviation for the term 'Carbon Capture and Sequestration'.

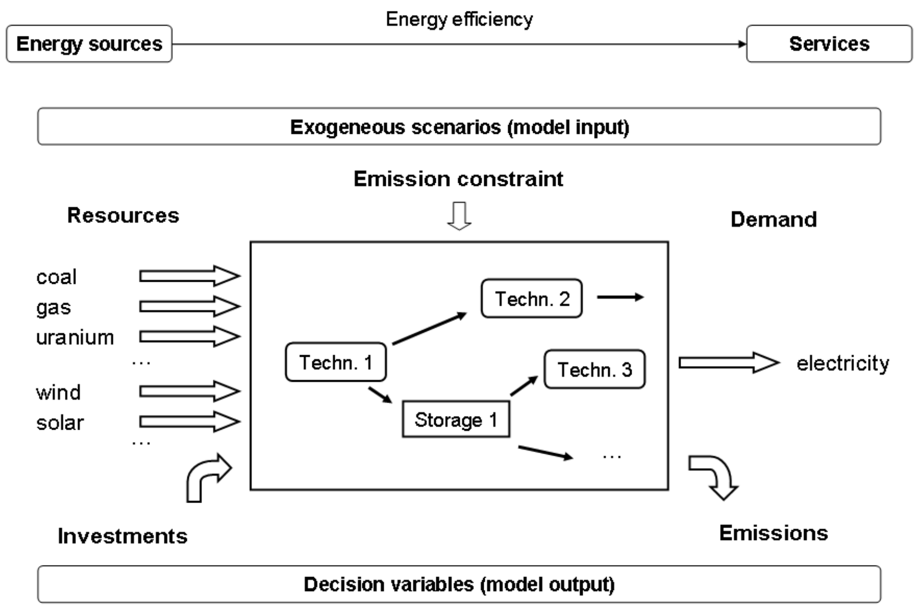

Figure 1.3: Schematic overview of the genEris model structure.

Due to the limited resource base of fossil fuels, sooner or later this transition will have to take place anyway, independant of the issue of climate change. What remains unclear is whether it takes place sooner or later, and which path will be used to achieve it. Which options should be used? Which one is optimal? What is 'optimal' anyway?

From an economists' point of view, the optimal solution is the one that yields the highest benefits, and if no benefits are to be gained, the one that minimize the losses. From the view of the social planner, the maximization of economic benefits would be replaced by the maximization of social welfare.

Apart from the difficulties that arise due to the definition of welfare, it is necessary to confine the range of effects that is taken into account. This holds for each modeling exercise. Does the modeler take into account the damages (or benefits) due to climate change? Will it be considered that the economy might adjust its demand to changing conditions? Can it be assumed that decisions are made by a fictitious planner who has unlimited forsight?

Figure 1.3 shows the basic structure of the energy system model that was used for this study. The objective of the model is to provide services (electricity demand) by using a limited amount of energy sources. Different technology options are available to access these resources. The range of possible solutions is limited by exogeneous restrictions (demand scenario, limited resources, and a cap on emissions). Inside this feasible solution space, the model 'decides' which technological options will be chosen by investing in the respective technologies. It determines an 'optimal' solution by minimizing the total discounted energy system costs.

1.3 Objectives and scope of this study

The objective of this study was to assess the different options of mitigating CO_2 emissions in the electricity sector. To achieve this, experiments with a global bottom-up energy system model were performed.

The model was designed on the basis of a large model of the complete energy system that had been created with the modeling toolbox genEris[3]. The electricity sector of this large model has been separated and modified to suit the needs of this study.

The model incorporates the fossil fuel sector as well as the main mitigation options: Renewable energy, nuclear energy and CCS. A complex representation of the nuclear energy fuel chain with two different reactor designs (fast and nuclear reactors) was developed.

To assess the behaviour of the model subject to different parameter assumptions a sensitivity analysis of important key parameters has been performed. To achieve this, the model code has been modified to link it to SimEnv, a tool for designing and performing multi-run experiments.

Additionally, an extensive set of MATLAB scripts has been developed to faciliate the graphical vizualization of model results.

The selection of technologies and their parametrization does not claim to be complete. The scope of the model is generic to a certain extent. Each technological option can be interpreted as a representative of a broader range of similar technologies. The intentional simplicity of the model makes it easier to understand its behaviour, and the results obtained from working with it indicate which directions should be chosen for further research.

[3]genEris is a tool for the creation of energy system models that is currently being developed at the PIK institute.

1.4 Structure of this document

This section gives an overview of the following parts of this document.

- *Chapter 2 – Energy System modeling:* In this part the methods and materials that were used are presented. It is divided into several sections:
  - Section 2.1 introduces the modeling tool *genEris*, covering its main characteristics, its abilities and limitations and the mathematical structure of the model equations.
  - Sections 2.2 and 2.3 describe the technologies that are represented by the energy system model.
  - Section 2.4 covers the structure of the energy system model.
  - Section 2.5 describes the technological and economical parameters that have been used.
- *Chapter 3 – Results and discussion:* In this chapter the results of the performed experiments will be presented. It is divided into two parts:
  - Section 3.1 presents a set of representative single model runs and introduces the various types of results.
  - Section 3.2 covers several multi-run experiments that have been conducted to explore the effects of the variation of various model parameters.
- *Chapter 4 – Conclusions:* This chapter concludes with a summary of the main findings and recommendations for further studies.
- *Appendix:* This part contains a glossary of all symbols, abbreviations and units that have been used.

2 Energy System modeling

2.1 The modeling tool genEris

2.1.1 Overview

Reasons for designing yet another energy system modeling tool

Energy System Models (ESM) are widely used for the assessment of energy technologies and related policy proposals. They organise input and output data, implement equations and the computes scenarios. MARKAL/ANSWER (IEA, 2006) is a tool commonly used for energy system modelling. It provides a high-level programming language building on GAMS[1], which enables the user to define technologies, energy carriers *etc.* and to link them to form an ESM. Unfortunately, this tool is quite inflexible with respect to various needs, since it is proprietary software. In particular, the core of the modelling toolbox, which translates user specified information into GAMS code, remains a black-box to the modeler. This is justified as long as the modeler does not want to change the structure of the ESM of the MARKAL/ANSWER type. Such problems arise as soon as the modeler wishes to augment the model structure by a concept that is not covered by the MARKAL/ANSWER programming language. This is the case for the implementation of learning curves which imply the endogenous change of economic parameters for different technological options.

The modeling tool genEris represents a different, more flexible approach: It provides full access to all equations and features that are implemented. The goal of genEris is not to provide a fully integrated user-friendly system using graphical user interfaces like MARKAL/ANSWER but to introduce a flexible tool to develop ESM. The users are invited to augment the toolbox in order to meet their individual needs.

Structure of the model

Basic structure The energy system is modeled as a network of *technologies* and *energy types* resp. *quantities* which are connected by flows of energy and matter[2]. Figure 2.1 gives an overview on how technologies are represented. Each technology transforms one main input into one main output flow. Additional couple product or own consumption flows and emission flows (CO_2 or captured CO_2) can be defined. All flows are interconnected by linear coefficients.

Energy types are divided into three categories:

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[1]GAMS is a high-level modeling system for mathematical programming and optimization. It includes a collection of integrated solvers.

[2]The model represents both energy and mass flows, energy types and quantities. Nevertheless, for the sake of simplicity in this document the terms 'energy type' and 'energy flow' will be used from time to time without mentioning 'quantities' and 'mass flows'.

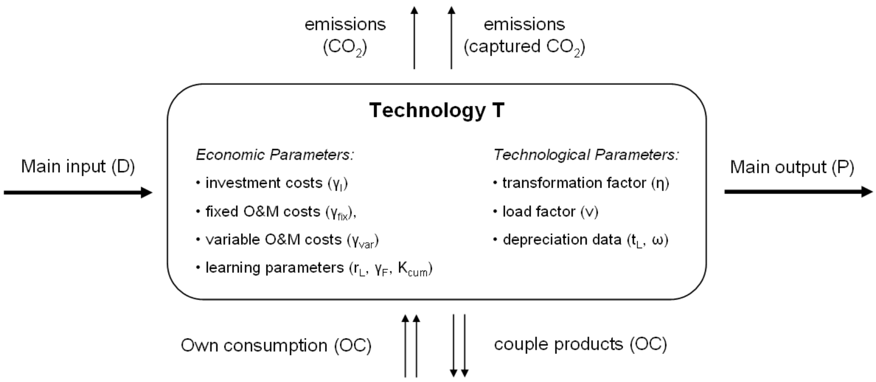


Figure 2.1: Representation of technologies in genEris. All parameters that are shown are defined exogeneously, with the exception of the investment costs of learning technologies which are expressed as a function of the cumulated capacity.

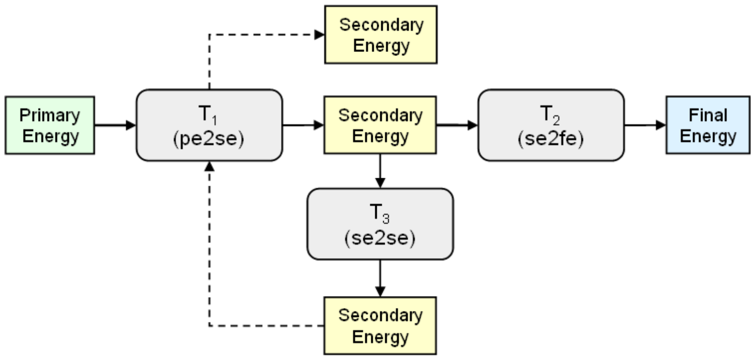


Figure 2.2: Basic structure of the transformation network in genEris. The solid arrows represent main input / main output flows, the dashed arrows couple products / own consumption flows. The acronyms (pe2se), (se2se) and (se2fe) name the mappings which represent the respective pathways in the model code. See section 2.1.1 for details.

- *Primary energy:* Primary energy sources, e.g. coal, gas or wind energy.
- *Secondary energy:* Intermediate energy types or quantities, e.g. electricity prior to being distributed to the end consumers, or irradiated fuel of nuclear reactors.
- *Final energy:* The 'end products' of the energy system, e.g. electricity that has been distributed via the electricity grid.

The basic structure of the model is a unidirectional transformation chain: Primary energy (which is subject to resource and potential constraints) is tranformed into secondary energy; secondary energy is transformed into final energy. The 'network' is created by technologies that transform one secondary energy type into another secondary energy type, and by couple product and own consumption flows, which lead to (or originate from) secondary energy types as well. Figure 2.2 shows the basic structure of this network.

Final energy types have exogeneous demands associated with them. The objective of satisfying these demands is the 'driving force' behind the transformation chain. For some quantities no demand exists – e.g. irradiated nuclear fuel. A maximum storage capacity is introduced for these quantities to 'force' the model to transform them into other products.

Capacities of technologies The transformation process via a certain technology is subject to capacity constraints: The main output flow at each timestep equals the installed capacity of the technology at this timestep, scaled down by load factors (for all technologies) and site-dependent availability factors (for renewable energy technologies). Technologies that are installed at a certain timestep have a limited lifetime after which they cease to operate.

Emissions and CCS CO_2 emissions are subject to an emission timepath constraint which prevents the annual emissions for each timestep to exceed an exogeneously defined level. Captured CO_2 is regarded as an emission as well. It is transformed via a chain of technologies (compression, transport via pipelines, injection into deposits and monitoring). Final CO_2 deposits are subject to cumulated capacity constraints.

Costs Four types of costs are represented: Specific investment costs, fixed and variable operation and maintenance costs for technologies, and specific extraction costs (fuel costs) for the use of exhaustible resources. Technologies can be defined as *non-learning*, in which case all cost parameters are constant, or as *learning*, in which case the investment costs are expressed as a function of the cumulated capacity[3].

Implementation All of the model equations are linear, with the exception of the learning equations. The model is written in GAMS. The model is solved with the integrated solver CONOPT3 which uses a nonlinear programming algorithm to find a local optimum.

In the following section the characteristics of technologies and primary energy sources will be discussed in detail.

Characteristics of transformation technologies

Each transformation technology is characterized by a set of economical and technological parameters that are defined exogeneously (see figure 2.1).

Economical parameters

- The *specific investment costs* describe the capital cost that needs to be invested to install a certain capacity of a technology. This payment is due once, immediately at the time when the new capacity is added. For non-learning technologies this parameter is constant and defined exogeneously. For learning technologies it is a function of the cumulated capacity. Details about the implementation of learning effects can be found in section 2.5.7.

[3] This also affects the fixed operation and maintenance costs as these are expressed as an annual share of the investment costs.

- The *specific operation and maintenance (O&M) costs* describe costs that occur during the regular operation of a technology. They include personnel costs, lease costs, costs caused by repair and maintenance activities, and all costs that are caused by consumption effects that are not internalized in the model. In genEris, the O&M costs are disaggregated into *fixed* and *variable* costs. Variable O&M costs are a function of the main output per time. Fixed O&M costs are calculated as a fixed percentage of the investment cost that is paid per year. The following example illustrates the difference between the two: Operating a nuclear power plant at full or partial load does only have little effect on the operation costs, because all security and monitoring systems need to be functional in any case. On the other hand, the operational costs of a wind turbine depend strongly on the mechanical stress that is put on the technical components like the rotor blades or the transmission system. The mechanical stress depends on the average wind speed and the power output.

Technological parameters

- The *transformation factor* η is defined as the ratio between main output and main input stream. For most power generation technologies the transformation equals the *efficiency factor*, i.e. the electricity that is generated per consumption of primary energy[4]. In this case, η has no unit and its values range between 0 and 1. However, in genEris not all technologies produce energy as a main output[5]. Some technologies transform one quantity into another, whereas the two quantities are measured with different units[6].

- The *load factor* ν: No technology can be operated at full load throughout all its lifetime without interruptions. Shutdowns periods or periods of operation at partial load can by caused by accidents or regular maintenance and repair issues. This effect is accounted for by the *load factor* ν which is defined for each technology. The potential of renewable energy sources varies statistically over time and site. Therefore, technologies that rely on these energy sources are always operating at partial load.

Learning effects In genEris *one-parameter learning curves* are used to describe the correlation between the cumulated investment efforts into a technology and its specific investment cost. The correlation is shown in equation 2.1.

$$C_I(t) = \gamma_F + \gamma_L \left(\frac{K_{cum}(t)}{K_{cum}(t_0)} \right)^{\alpha} \tag{2.1}$$

$$\alpha = \frac{\ln(1 - r_L)}{\ln 2} \tag{2.2}$$

[4]This might be the heating value of the consumed fuel for combustion technologies, or the solar irradiation for photovoltaic

[5]And it is not easy to determine the heating value of uranium

[6]For example, the technology `tnrdd` (Direct disposal of spent fuel from thermal nuclear reactors) transforms spent fuel, which is measured in mass units MtHM, into high level radioactive waste, which is measured in volume units $10^6 \mathrm{m}^3$. In this case, the transformation factor η describes how many m^3 of waste are generated by processing 1 tHM of spent fuel and its unit is $\mathrm{m}^3/\mathrm{tHM}$.

$C_I(t)$	Cost at time t
γ_F	Floor costs
γ_L	Learning Costs
$K_{cum}(t)$	Cumulated capacity at time t
r_L	Learning Rate (reduction of total costs due to doubling of K_{cum})

Three parameters define the relationship between change of cumulated capacity additions and change in investment cost:

- The *learning rate* r_L describes the relative decrease of investment costs that is achieved by doubling the cumulated capacity. It represents the *speed* of learning effects.
- The *floor costs* C_F are the part of the investment costs that cannot be reduced by learning.
- The *initial cumulated capacity* $K_{cum}(t_0)$ define how much experience has been accumulated *before* the period that is been investigated in the model.

Of these three, the learning rate is often treated as the one most important parameter, but figure 2.3 shows that all three parameters affect the shape of the learning curve significantly. The choice of the initial cumulated capacity poses a problem for technologies that are not yet in use at the beginning of the time horizon, because eq. 2.1 becomes infinite for $K_{cum}(t_0) = 0$.

Under which circumstances can this model approach be applied?

- $K_{cum}(t_0) = 0$ is not allowed -> technology must already be in use at t_0.
- Learning effects only work if many units are produced (optimization of processes that are repeated very often, standardization).
- Additional constraints need to be considered: resource constraints (silicium in photovoltaics), political frameworks (increasing security efforts for nuclear energy)

Characteristics of primary energy sources

In genEris, primary energy sources are divided in two categories:

- *Exhaustible* energy sources
- *Renewable* energy sources

For exhaustible energy sources, the limited resource base and the costs of extracting the resource is represented as follows:

The resource of each exhaustible primary energy type e_p is divided into grades g. Each grade g of resource e_p is defined by a maximum amount of energy or mass $\epsilon(e_p, g)$ that can be extracted from it, and by a specific extraction cost $\gamma(e_p, g)$.

For renewable energy sources, the limited potential of the energy source and its site-dependent availability is represented as follows:

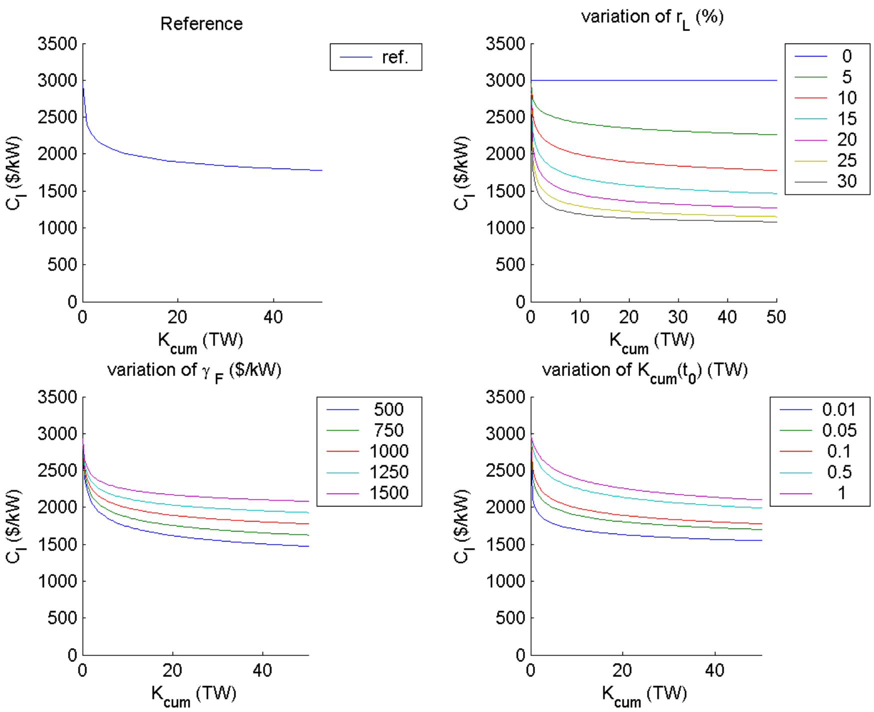


Figure 2.3: Learning curve parameters. The upper left figure shows the learning curve for a hypothetical technology (initial investment costs $C_I(t0) = 3000\,\$/\mathrm{kW}$, floor costs $\gamma_F(t0) = 1000\,\$/\mathrm{kW}$, learning rate $r_L = 10\,\%$). In the other three figures, the effects of the variation of one single learning parameter is shown, while keeping the other parameters constant.

The total potential for each technology T_{ren} that uses a renewable energy source is divided into grades g. Each grade g of the technology T_{ren} is defined by a maximum amount of secondary energy $\pi(T_{ren}, g)$ that can be produced by using it, and by an availability factor $\nu_R(T_{ren}, g)$. The availability factor describes the energy output per time that is generated by a certain installed capacity of technology T_{ren}.

Sets and mappings

A few explanations about a few language elements of GAMS are necessary to understand the way how the system of model equations is generated. This section will introduce the concepts of sets, subsets and mappings.

Sets and subsets In GAMS, a set is a one-dimensional list of items. For example, all energy types in genEris are defined in the set `enty`. Subsets contain selected elements of another set. For example: All primary energy types are defined in the subset `pety(enty)`.

Mappings Mappings are multi-dimensional combinations of set elements. An example: All transformation pathways that link primary energy types with secondary energy types are defined in the mapping `pe2se`, which is defined as follows:

```
pe2se(pety(enty), sety(enty), te)
        / pegas.seel.ngcc
        .
        .
        .
        /;
```

Each element of `pe2se` consists of a combination of one primary energy type `pety`, one secondary energy type `sety` and the technology `te` that transforms the former into the latter. In this example, *gas* (`pegas`) is transformed into *electricity* (`seel`) via the *natural gas combined cycle* technology (`ngcc`).

Sets, subsets and mappings can be used for indexing variables, parameters and equations. For example, the equations that describe the transformation of primary energy to secondary energy types (`pe2setrans`) are defined for the set `t` and the mapping `pe2se`. This way, the equation appears only once in the GAMS model code, and when the code is compiled, one equation for each timestep and each transformation pathways between primary and secondary energy types is generated. This approach makes it easy to change the structure of the energy system without rewriting the equation definitions: If, for example, a new technology is introduced, it is only necessary to add it to the respective sets and mappings, define the parameters that characterize it, and the required additional equations will be generated automatically when the model code is compiled.

2.1.2 The algebraic structure

As the modification and extension of the model structure formed an important part of this study, the algebraic model structure will be presented in a fairly detailed way. Nevertheless, an complete and exhaustive description would not meet the scope of this document. A complete documentation of the model can be found in Bauer und Lueken (2006).

Figure 2.4 gives a graphical overview of the mathematical structure of the genEris model. This figure is used to guide through the description of the algebraic model structure.

Each rectangular block represents one type of equation in the model. Different content sections of the model are coded by color. The black lines represent flows of information (if a variable appears in two equations, they are connected by a line). Coloured lines represent flows of energy and quantities. Selected parameters that represent exogeneous constraints are represented by blue ovals.

Naming conventions The naming of variables and other model elements follows some general rules[7]: Greek letters are used for model parameters, big latin letters for model variables. Small latin letters are used for sets and subsets. Mappings are represented by letter M. As far as possible, variable names are explained in the descriptive text when they are mentioned the first time. A complete list of used symbols can be found in the appendix (tables A.1 – A.4). Table A.7 contains a list of the abbreviations that were used for the equations.

Objective function and cost equations

At the top of figure 2.4 the objective function (`goallp`) is shown which calculates the total energy system cost Z. The optimal solution of the equation system is determined by minimizing Z.

Objective function (`goallp`)

Eq. 2.3 shows the *objective function* (`goallp`): Z is the sum of fuel costs C_F, investment costs C_I and the sum of fixed and variable operation and maintenance costs C_O, aggregated and discounted over all timesteps. Δt is the time step length[8], ρ is the annual discount rate.

$$Z = \sum_{t=t_0}^{t_{end}} e^{-\rho(t-t_0)} \Delta t (C_{FU}(t) + C_I(t) + C_O(t)) \tag{2.3}$$

Fuel costs (`ccostfu`)

The *fuel costs* are calculated by equation 2.4 (`ccostfu`). The fuel costs $\tilde{C}_F$ for each timestep t, primary energy type e_p and resource grade g are calculated as the product of the extraction from the respective resource grade $\tilde{P}_p(t, e_p, g)$ and the specific fuel cost coefficient $\iota(e_p, g)$:

$$\tilde{C}_F(e_p, g, t) = \iota(e_p, g) \cdot \tilde{P}_p(t, e_p, g) \qquad \forall\ t\ \ \forall\ e_p, g \tag{2.4}$$

[7] With the occasional exception.

[8] All time-specific values are defined per year. Therefore, to calculate the costs per timestep, the annual costs need to be multiplied with the timestep length.

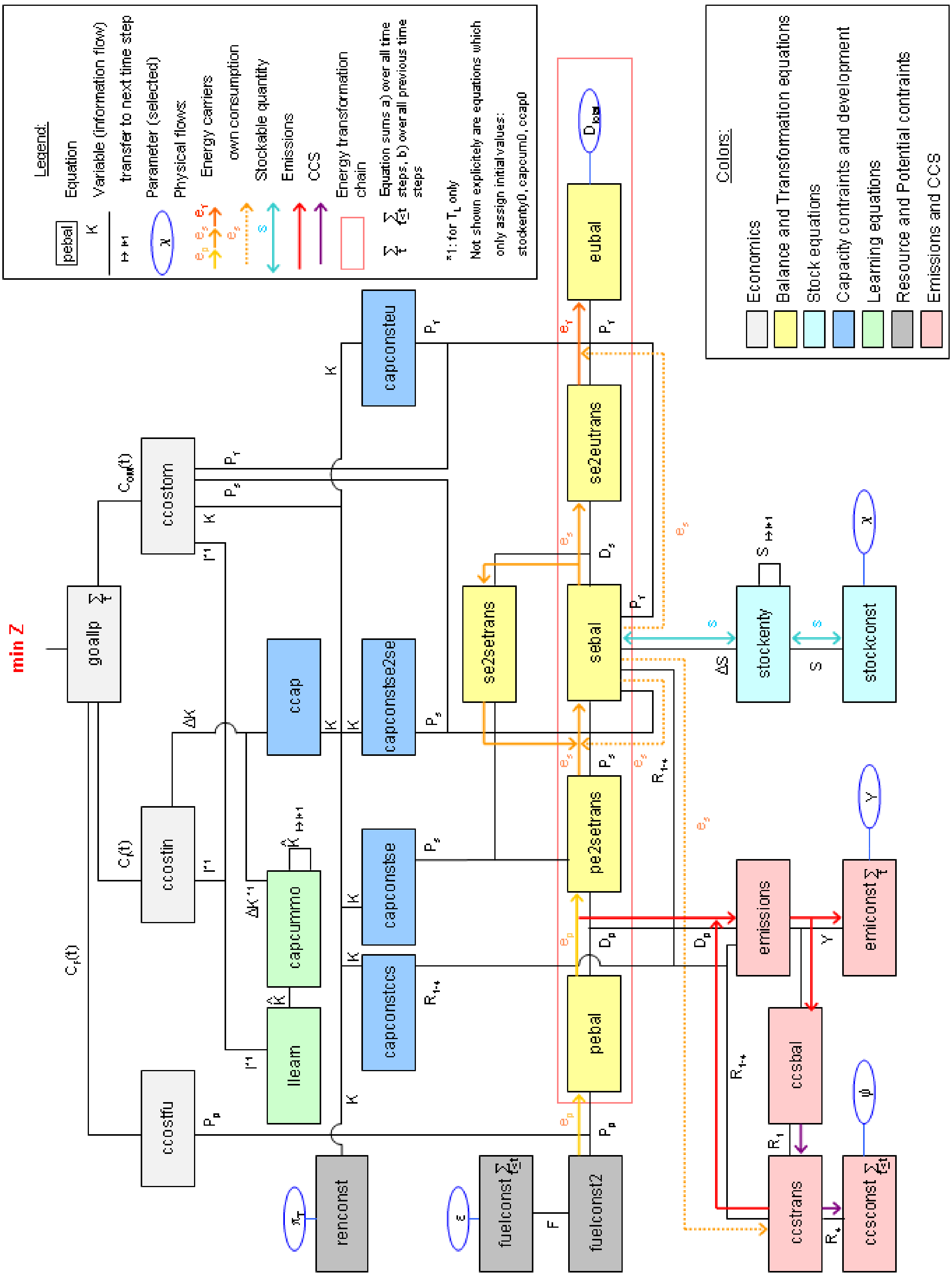


Figure 2.4: Overview of the algebraic structure of genEris (Bauer und Lueken, 2006). See table A.7 for a list of equation names, and tables A.1 and A.3 for a list of variable and parameter names.

The *total* fuel costs C_F for each timestep t are calculated by summation over the fuel costs for all primary energy types and grades:

$$C_F(t) = \sum_{e_p} \sum_{g} \tilde{C}(t, e_p, g) \qquad \forall\ t \tag{2.5}$$

Investment costs (`ccostin`)

An increase of capacity $\Delta K(t,T)$ of technology T at timestep t results in investment costs $\tilde{C}_I(t,T)$:

$$\tilde{C}_I(T,t) = \gamma_L(T,t) \cdot \Delta K(T) \qquad \forall\ t\ \ \forall\ T \tag{2.6}$$

The specific investment costs $\gamma_I(T,t)$ are constant for non-learning technologies. For technologies where learning effects are considered they are a function of the cumulated capacity $K_{cum}(t)$ and the respective learning parameters (see section 2.1.1). The *total* investment costs C_I for timestep t are calculated by summation over all technology types:

$$C_I(t) = \sum_{T} \tilde{C}_I(t,T) \qquad \forall\ t \tag{2.7}$$

Operation and maintenance costs (`ccostom`)

The operation and maintenance costs $\tilde{C}_O$ for a technology T at time t consist of two factors:

The *fixed* operation and maintenance costs are a function of the available capacity of the respective technology $K(t,T)$ and its specific investment costs $\tilde{C}_I(t,T)$. The *variable* operation and maintenance costs are a function of the main output of the respective technology $P(t,T)$. The linear relationship is expressed by the coefficients γ_{fix} and γ_{var}.

$$\tilde{C}_O(t,T) = \gamma_{fix}\tilde{C}_I(t,T)K(t,T) + \gamma_{var}P(t,T) \qquad \forall\ t\ \ \forall\ T \tag{2.8}$$

The *total* operation and maintenance costs for timestep t are calculated by summation over all technology types:

$$C_O(t) = \sum_{T} \tilde{C}_O(t,T) \qquad \forall\ t \tag{2.9}$$

Balance and transformation equations

These equations describe the energy and mass flows inside the network of energy types and technologies.

Balance equations (`pebal`, `sebal`, `eubal`)

The general structure of the balance equations is as follows:

For each energy type e and each timestep t the sum of all input streams (called *production* P) equals the sum of all output streams (called *demand* D) plus a storage term ΔS.

$$\sum_{all} P(e) = \sum_{all} D(e) + \Delta S(e) \qquad \forall\, t \tag{2.10}$$

In the summation, *all* means all possible ways of energy transformation relevant for the respective energy type – including main input and output flows as well as own consumption and couple production flows.

In genEris there exist three balance equation types `pebal`, `sebal` and `eubal` for the three main subsets of energy types (*primary*, *secondary* and *final* energy). All three of them follow the structure of equation 2.10, but different input and output flows are included.

Balance equations for primary energy types (`pebal`)

Each primary energy resource is divided into different grades g. At each timestep t, the demand D_p for each primary energy type e_p equals the aggregated production of e_p of different resource grades g:

$$\sum_{M_{ep,g}} \sum_{M_{p\to s}} P_p(t, e_p, e_s, T, g) = \sum_{M_{p\to s}} D_p(t, e_p, e_s, T) \quad \forall\, t \;\; \forall\, e_p \tag{2.11}$$

Primary energy types cannot be stored, so there is no storage term in this balance equation.

Balance equations for secondary energy types (`sebal`)

This equation looks slightly confusing because in the model code the input and output flows are organized in several different mappings. For each secondary energy type e_s and each timestep t, the production of e_s equals the demand for e_s plus a storage term ΔS. There are separate terms for production and demand flows, according to their origin or destination: there are main output flows originating from primary energy types ($M_{p\to s}$) and other secondary energy types ($M_{s\to s}$), and there are couple production flows (M_{own})[9]. Demand flows are divided into main output flows leading to final energy types ($M_{s\to f}$) and other secondary energy types ($M_{s\to s}$), and into own consumption flows (M_{own}). Own consumption and couple production flows are linked to the production by the respective technology via the *onw consumption coefficient* ξ[10].

The storage term ΔS is zero for energy types that cannot be stored.

[9] Own consumption flows ar modeled as couple production flows with a negative couple production factor ξ. Therefore only one term for both flow types appears in the balance equation.

[10] ξ is positive for couple production and negative for own consumption.

$$
\begin{aligned}
& \sum_{M_{p\to s}} P_s(t, e_p, e_s, T) + \sum_{M_{s\to s}} P_s(t, e_{s'}, e_s, T) \\
+ \quad & \sum_{M_{own}} (\xi(e_p, e_{s'}, T, e_s) \cdot P_s(t, e_p, e_{s'}, T)) \\
+ \quad & \sum_{M_{own}} (\xi(e_{s'}, e_f, T, e_s) \cdot P_f(t, e_{s'}, e_f, T)) \\
= \quad & \\
& \sum_{M_{s\to f}} D_s(t, e_s, e_f, T) + \sum_{M_{s\to s}} D_s(t, e_s, e_{s'}, T) \\
+ \quad & \Delta S(t, e_s) \qquad \forall\ t\ \ \forall\ e_s \qquad (2.12)
\end{aligned}
$$

Balance equations for final energy types (`eubal`)

At each timestep t, the external demand D_{ex} for final energy type e_f must be equaled by the aggregated production P_f of e_f:

$$
\sum_{M_{s\to f}} P_f(t, e_s, e_f, T) = D_{ex}(t, e_f) \quad \forall\ t\ \ \forall\ e_f \qquad (2.13)
$$

$$
M_{s\to f} = (e_s \times e_f \times T) \in \mathfrak{M}_{s\to f}
$$

Final energy types cannot be stored, so there is no storage term in this balance equation.

Transformation equations (`pe2setrans`, `se2setrans`, `pe2eutrans`)

Each technology T transforms a main input stream of one energy type j (*demand* D_j) into a main output stream of a different energy type k (*production* P_k). These two streams are linked by the transformation factor $\eta(T)$.

$$
\eta(T) \cdot D_j(t, T) = P_k(t, T) \quad \forall\ t\ \ \forall\ T\ \ j, k \in e_p, e_s, e_f \qquad (2.14)
$$

As the transformation pathways are defined via different mappings, in genEris there exist three different types of transformation equations. All of them follow the general structure of equation 2.14 and will not be explained in detail.

Stock equations

Some secondary energy types s can be stored. For these a storage term $\Delta S(t, s)$ in the secondary energy balance equation exists. Two equations deal with the development and the constrictions of stocks:

Stock change (`stockenty`)

For each succeeding timesteps t and $t{+}1$, the stock of quantity s changes by the difference $\Delta S(t, s)$:

$$S(t+1,s) = \Delta t \cdot \Delta S(t,s) + S(t,s) \qquad \forall\ t\ \ \forall\ s \tag{2.15}$$

At the first timestep t_0 all stocks are set to the initial value of 0.

Constraint on stock capacities (`stockconst`)

For each quantity that can be stored there exists a constraint on the maximum storage capacity. This constraint is not time-dependent, and it cannot be changed endogeneously. At each timestep t the stored amount of energy s must be smaller or equal to the maximum storage capacity $\chi(s)$:

$$S(t,s) \leq \chi(s) \qquad \forall\ t\ \ \forall\ s \tag{2.16}$$

Capacities: Constraints and development

Capacitiy constraints on production (`capconstse`, `capconstse2se`, `capconsteu`, `capconstccs`)

The installed capacity of a technology determines how much energy can be transformed by this technology. For all technologies, the installed capacity is scaled down by the availability factor ν. For renewable energy technologies, capacities are additionally scaled down by the resource availability factor ν_r that distingushes different resource grades from each other.

$$P_s(t,e_p,e_s,T) = \sum_{M_{T_s \leftrightarrow g}} \sigma(T) \cdot \nu(T) \cdot \nu_r(T,g) \cdot K(t,T,g) \quad \forall\ t\ \ \forall\ M_{p \rightarrow s} \tag{2.17}$$

As the transformation pathways are defined via different mappings, in genEris there exist four different types of capacity constraint equations . All of them follow the general structure of equation 2.17 and will not be explained in detail.

Increase and depreciation of capacities (`ccap`)

In genEris the lifetime of a technology is described by two factors. First, each technology has a *technical lifetime* t_l. The technical lifetime describes the time period after which capacity additions are fully depreciated. Different approaches can be used to describe what happens in between, as shown in figure 2.5. At the moment genEris supports exponential and vintage depreciation schemes. In this study the *vintage* depreciation scheme was used for all technologies, i.e. the depreciation curve is defined by assigning a depreciation parameter $0 < \omega < 1$ for each timestep of the technical lifetime of a technology.

The installed capacity $K(t,T)$ of technology T at timestep t is the sum of all capacity additions ΔK at the previous timesteps, multiplied with the respective depreciation factors ω:

$$K(t,T,g) = \sum_{M_{T \leftrightarrow t_l}} \Delta t \cdot \omega(t_l,T) \cdot \Delta K(t-t_l,T,g) \quad \forall\ t \tag{2.18}$$

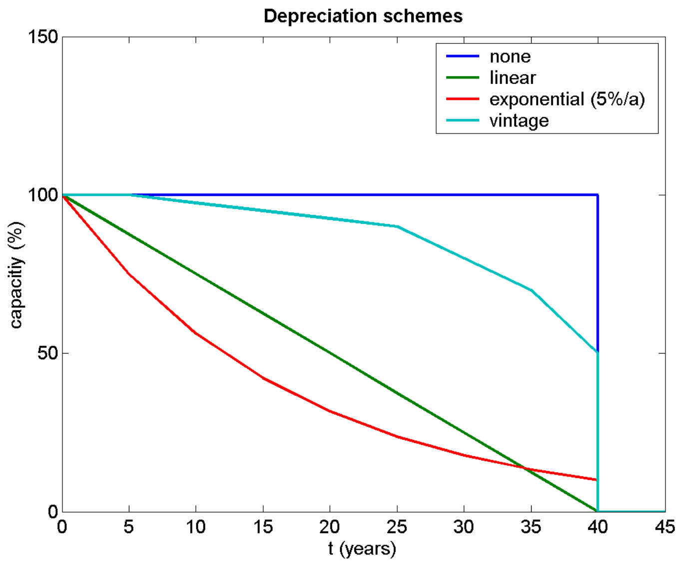


Figure 2.5: Depreciation schemes

Learning equations

The investment costs of learning technologies T_L are expressed as a function of their cumulated capacity. The learning approach that is applied in genEris has been explained in section 2.5.7. In the model code, investment costs of learning technologies are calculated in equation `llearn` which is equivalent to equation 2.1.

The cumulated capacity $K_{cum}(t)$ are calculated in equation `capcummo` as the sum of all capacity additions at previous timesteps:

$$K_{cum}(t+1,T) = \Delta t \Delta K(t,T) + K_{cum}(t,T) \quad \forall\ t\ \ \forall\ T \tag{2.19}$$

The initial cumulated capacities $K_{cum}(t_0)$ are defined exogeneously.

Constraints on resources and potentials

Extraction constraint for exhaustible resources (`fuelconst`)

For each timestep t the cumulated extraction F of exhaustible primary energy type e_x of resource grade g must not exceed an upper limit $\epsilon(e_x, g)$ that is set exogeneously:

$$\sum_{t'=t_0}^{t} \Delta t \cdot F(t', e_x, g) \leq \epsilon(g, e_x) \quad \forall\ t \tag{2.20}$$

Production and cumulated extraction (`fuelconst2`)

For each timestep t the total production P_p of exhaustible primary energy type e_x of resource grade g equals the extraction from the respective resource and grade:

$$\sum_{M_{p\to s}} P_p(t, e_x, e_s, T, g) = F(t, e_x, g) \quad \forall\, t \tag{2.21}$$

Potential constraint for renewable energy sources (`renconst`)

For renewable energy sources, at each timestep t the secondary energy that is produced by grade g of resource e_r must not exceed an upper limit π_e that is set exogeneously:

$$P_s(t, e_r, g) \leq \pi_e \quad \forall\, t \;\; \forall\, e_r, g \tag{2.22}$$

Emissions and CCS

Production of emissions (`emissions`)

In genEris, technologies that transfer primary to secondary energy can be defined as producers of emissions. The respective transformation pathways are members of the mapping $M_{T\to Y}$. For each timestep t, each technology T and each emission type y, the emissions Y are calculated as the product of the demand for primary energy D_p and the specific emission coefficient λ.

$$Y(t, T, y) = \sum_{M_{T\to Y}} \lambda(e_p, e_s, T, y) \cdot D_p(t, e_p, e_s, T) \quad \forall\, t \tag{2.23}$$

In the model that was used for this study, CO_2 and captured CO_2 are the only available emission types.

Constraint on CO_2 emissions (`emiconst`)

For each timestep t the cumulated emissions of CO_2 by all technologies T must not exceed an upper limit $Y_{max}(t)$ that is set exogeneously:

$$\sum_{T} Y(t, T) \leq Y_{max}(t) \quad \forall t \tag{2.24}$$

The CCS module (`ccsbal`, `ccsconst`, `ccstrans`)

Captured CO_2 is generated as an emission during transformation of primary energy to secondary energy types. It is then passed through a chain of transformation processes that consists of compression, transportation via pipelines, injection into a repository and monitoring of the sequestrated CO_2.) Three equation blocks describe the mass balances, the transformation processes and the constraint on available repositories. As these equations have not been modified during this study, they will not be described in detail here.

Initial calibration

The initial strucure of the energy system needs to meet two demands: First, the installed capacities of all technologies must be chosen in a way that the production of energy meets both the external demand for final energy and the internal demand for secondary energy. Second, a *spin-up* of the inital capacities needs to be performed.

Initial capacities For each technology an initial share coefficient κ_0 defines the relative contribution of its main output stream to the total production of the respective quantity at timestep t_0. The parameters κ_0 are normalized to add up to 1 for each quantity. Given these *relative* shares, a linear equation system that consists of equations 2.25 and 2.26 is used to calculate the *absolute* initial capacities that are necessary to satify all internal[11] and external initial demands.

Equation 2.25 calculates the total initial demand D_{tot} for each energy type e as the sum of the external demand D_{ex} and the sum of all demands by transformation pathways for which energy type e is the main input minus the sum of couple production and own consumption pathways that produce or consume energy type e:

$$\begin{aligned} D_{tot}(t_0, e) &= D_{ex}(t_0, e) \\ &+ \sum_{M_{e \to e}} \frac{\nu(T)\nu_g(1,T)}{\eta(T)} K(t_0, T) \\ &- \sum_{M_{own}} \xi(T)\nu(T)\nu_g(1,T)K(t_0,T) \qquad \forall\, e. \end{aligned} \tag{2.25}$$

It is assumed that renewable energy technologies use the first (best) potential grade.

Equation 2.26 calculates the absolute initial capacity K for each technology as a function of the initial demand for its output energy type e, scaled by its initial share coefficient κ_0 and its transformation factors.

$$K(t_0, T) = \frac{\kappa_0(T)}{\nu(T)\nu_g(1,T)} D_{tot}(t_0, e) \qquad \forall T. \tag{2.26}$$

These two equations form a square system of linear equations with a unique solution that is solved using the CONOPT3 solver prior to solving the main model.

Spin-up of capacities genEris does not assume that all initial capacity is constructed at the initial timestep t_0, but during a *spin-up period* before the time horizon that is covered by the model. This time period prior to the first model timestep is refered to as *spin-up period* t_{su}. A set of spin-up coefficients $\sigma(t_{su}, T)$ is defined for each technology that describes the increase of installed capacity during this period. The parameters are normalized to sum up to 1 for each technology. The capacity K of each technology T for each timestep of the spin-up period $t \in t_{su}$ is calculated following equation 2.27.

$$K(t, T) = K(t_0, T)\frac{\sigma(t,T)}{\omega(t,T)} \qquad \forall t \in t_{su}, T. \tag{2.27}$$

[11] Internal demands result from own consumption of technologies. Also, couple production needs to be taken into account by substracting its amount from the direct production that is needed.

2.1.3 Modifications of the model structure that were applied during this study

Integrating the nuclear fuel cycle model into genEris

Before this study was carried out, the representation of technologies with more than one input and/or output flow was not fully implemented in genEris. However, this feature is essential for the design of the nuclear energy module as it was used (see figure 2.13 for a graphical representation of this module). The realization of this design did not only require the creation of new technologies and transformation pathways by extending the existing sets and mappings, but also some structural modifications:

- For technologies that transform one secondary energy type into another secondary energy type, a separate transformation equation (`se2setrans`) and a capacity constraint equation (`capconstse2se`) were added, and new terms were added to the secondary energy balance equation `sebal`.
- The feature of storing quantities was added. This required a storage term in the secondary energy balance equation and the creation of new variables and equations for the initialization and cumulation of stocks as well as for the constraints of maximum storage capacities.
- The linear equation system for the calibration of initial capacities has been rewritten completely to take into account the new energy and quantity flows.

Linking genEris and SimEnv

SimEnv is a tool for designing and performing multi-run sensitivity analysis experiments. Information about the experiment is defined in a set of configuration scripts. According to these scripts, SimEnv modifies the experiment parameters by inserting code into the model source files. The results from the model runs are collected and exported in a clearly defined format. To establish the link between SimEnv and the genEris model, several modifications were necessary:

- Some formal modifications were necessary to make the model conform with SimEnv file name conventions for model files etc.
- To enable SimEnv to apply changes to the model parameters, a set of new parameters was introduced that were used as scaling coefficients for model parameters or as switches for turning model options on and off A wide range of parameters can now be controlled during SimEnv experiments.
- Part of the model output was reorganized to make the exported data compatible with SimEnv requirements[12].
- The parametrization of the grading of exhaustible resources was redesigned so that maximum extraction and cost data for each grade are now calculated internally from a set of exogeneously defined Rogner curve parameters. This was done to reduce

[12] For example, the maximum number of dimensions for variables that are exported to SimEnv is 4. genEris results are stored in variables with up to seven dimensions.

the information of the complete cost-extraction curve to a minimum number of parameters that can be controlled by SimEnv.

Other modifications

- The emission constraint in the form of a maximum emission pathway with a cap for every timestep was added. It replaced a total cap for the intertemporally cumulated emissions.
- Demand scenarios with a non-constant annual growth rate were implemented. They replaced demand scenarios with constant exponential growth.
- As the model represents a wide range of energy and quantity flows and transformations, the variety of units that are used for different parameters can lead to some problems. A unified unit management system was implemented. Its basic idea is that the model structure requires a well-defined unit definition for each parameter value that is introduced. These two elements, parameter value and unit, are linked by the model code and can be exported automatically. The basic structure of this feature has been completed, but it still leaves some work to do.

2.2 Nuclear energy

This section deals with the process of using nuclear chain reactions to generate electricity. In section 2.2.1 a short introduction into the physical principles will be given. Sections 2.2.3 and 2.2.4 describe the different reactor technologies and the structure of the nuclear fuel cycle. The way nuclear energy is represented in the energy system model will be discussed in section 2.4.2.

For detailed information about nuclear energy the reader is asked to refer to the respective literature. A few recommendations:

- A good reference for *nuclear physics* (in german language) is Mayer-Kuckuck (1994).
- A highly regarded interdisciplinary study about future scenarios of various nuclear options that includes a detailed economical analysis is MIT (2003).
- Matthes (2006) gives a *critical view* on various aspects of nuclear energy.
- van Leeuwen und Smith (2005) performs a complete energy balance of the fuel chain for thermal reactors.
- An easy-to-read *glossary* of nuclear terms that is available online is Koelzer (2006).

2.2.1 Nuclear reactions

There are two basic categories of nuclear reactions that can be used to generate energy: nuclear *fusion* and nuclear *fission* reactions.

In fusion processes, multiple light nuclei join together to form one heavier nucleus. Current research is being done on developing a nuclear fusion reactor (for example the ITER

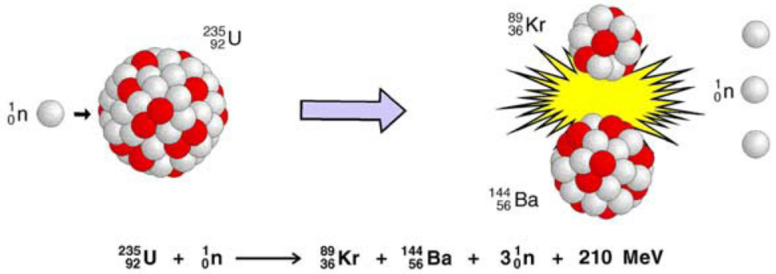


Figure 2.6: Nuclear fission reaction: A ^{235}U nucleus is hit by a neutron and splits into smaller nuclei plus three free neutrons (Koelzer, 2006).

project in France). However, his technology is not expected to be available on a commercial scale during the next 50 years. For this study, nuclear fusion is not taken into account as a technological option.

At present, the process of nuclear fission is the basis for the usage of nuclear energy. Nuclear fission occurs when a nucleus splits into two or more smaller nuclei. This process generates various types of radiation and a release of thermal energy due to the difference of binding forces between the particles of the orginial and the resulting nuclei.

Nuclei can split without external impacts. This process is referred to as *spontaneous fission*, which is a form of radioactive decay. The frequency of spontaneous fission events is determined by the binding forces that are acting between the different particles which make up a nucleus. As these forces are weaker in nuclei that consist of many particles, heavy elements are most likely to undergo fission. The *half life period* describes the period after which the mass of an isotope has diminished by half due to spontaneous fission.

During fission reactions, free neutrons are generated. A fission process can be *induced* when a nucleus is hit by a free neutron. If lots of these isotopes are packed tightly together (and hence, the *critical mass* is reached), a nuclear chain reaction can be started where the neutrons generated by one fission incident hit other nuclei which also undergo fission while generating more free neutrons, and so forth. This process is shown in figure 2.6.

The function of nuclear reactors is based on sustaining a nuclear chain reaction. The thermal energy that is released by the fission reaction is transferred to a *coolant* (water. gas or molten metal). It is then used to generate steam which drives a turbine and a generator.

2.2.2 Thermal and fast reactors

A few more details are necessary to understand how the two basic reactor designs (*thermal* and *fast* reactor) are working, and what type of fuel is used for each one.

The propability that a nuclear fission is induced when a nucleus is hit by a free neutron depends on the physical characteristics of the nucleus and on the kinetic energy of the neutron. The characteristics of different isotopes of the same element differ significantly.

Elemental isotopes can be categorized on how they react when they are hit by a free neutron. This behaviour also determines how they can be used in nuclear reactors:

Table 2.1: Characteristics of uranium isotopes ^{235}U and ^{238}U

	^{235}U	^{238}U
Fuel base for which reactor?	thermal reactor	fast reactor
Concentration in uranium ore?	0.7 %	99.3 %
Fissile?	yes	no
Undergoes spontaneous fission?	yes	no
Able to reach criticality?	yes	no
Reaction when hit by slow neutrons?	fission	-
Reaction when hit by fast neutrons?	-	neutron capture, transmutation to fissile ^{239}Pu

- *Fissile* isotopes can split when they are hit by a slow neutron. These isotopes can be used to sustain a nuclear chain reaction in thermal reactors. The most important fissile isotopes are uranium ^{235}U and plutonium ^{239}Pu.
- *Fertile* isotopes will absorb free neutrons, and the reaction product is itself a fissile isotope. ^{238}U is a fertile isotope.

The most important element that is used for the production of nuclear fuel is *uranium*. Natural uranium consists mainly out of two different elemental isotopes (^{235}U and ^{238}U). The ^{235}U content of natural uranium is very small (0.7 %). Table 2.1 gives an overview of the characteristics of the two isotopes.

Figure 2.7 displays the 'fisson behaviour' of ^{235}U and ^{238}U. The horizontal axis displays the kinetic energy of the free neutron (increasing from left to right), and the vertical axis represents the fission propability. The different lines represent the different isotopes and different types of nuclear reactions. Three basic messages that can be taken from this graphic:

- For reactions of ^{235}U (the line with the annotation '^{235}U(n,f)') the propability is highest if the kinetic energy of the neutron is low. These neutrons are referred to as *slow* or *thermal*.
- For reactions of ^{238}U (the line with the annotation '^{238}U(n,f)') the propability is highest if the kinetic energy of the neutron is high. These neutrons are referred to as *fast*.
- The reaction propability is much higher for ^{235}U than for ^{238}U[13].

These messages give insight into the two possible principles that are used to sustain a uranium-based chain reaction:

Thermal reactors These reactors are based on the fission of ^{235}U. Because the fission propability for this isotope is quite high, and because ^{235}U has a reatively high propability

[13] Note the logarithmic scaling on both axes.

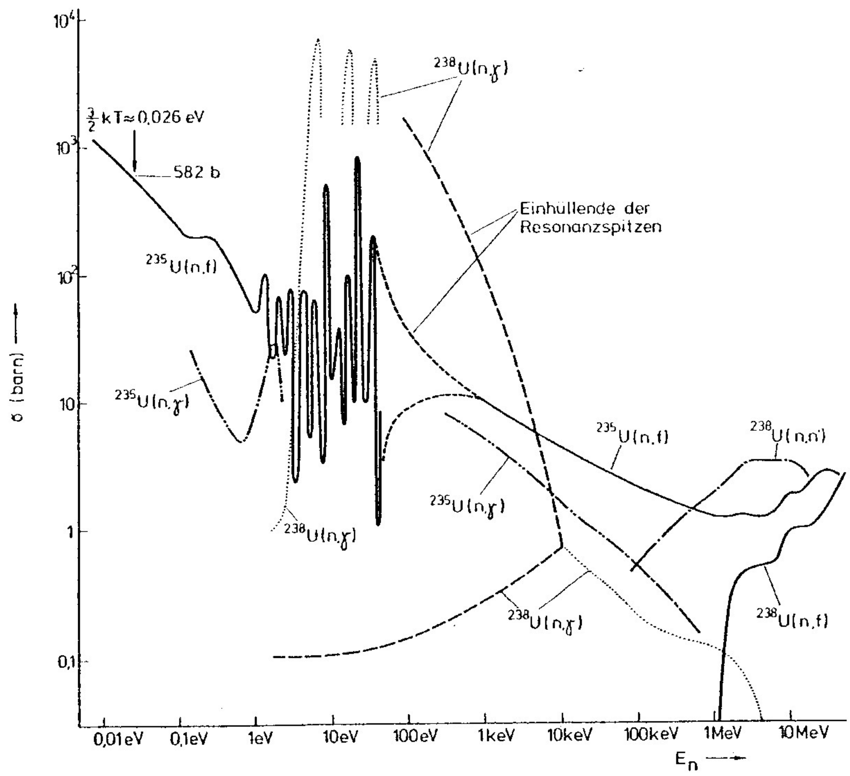


Figure 2.7: This figure shows the propability (vertical axis) for uranium isotopes to undergo fission or absorb a neutron when they are hit by neutrons with different kinetic energy (horizontal axis). Mayer-Kuckuck (1994).

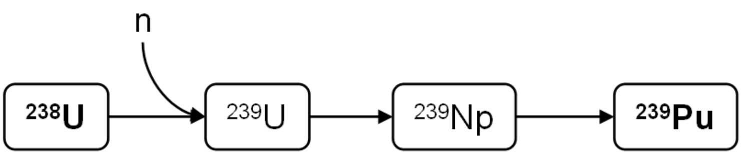


Figure 2.8: The 'breeding' process that occurs in fast reactors: a ^{238}U atom absorbs a neutron and is transmuted into fissile ^{239}Pu.

of undergoing *spontaneous* fission, a critical mass is achieved with low isotope densities[14]. However, free neutrons are very fast when are generated during a fission process, so they need to be slowed down to increase the fission propability. In thermal reactors this is achieved by inserting a *moderator* into the reactor core that slows neutrons down as they pass through it. *Water* is a very good moderator, other reactor designs use *graphite*.

Fast reactors The chain reaction in fast breeders is based on ^{238}U. This isotope is not fissile, but if it is hit by a fast neutron, it can absorb this neutron and transmute into the fissile plutonium isotope ^{239}Pu (see figure 2.8). Because ^{238}U is more likely to absorb fast neutrons, fast reactors do not have moderators as thermal reactors do.

As ^{238}U is not itself fissile it cannot achieve criticality and therefore, it cannot be used as a reactor fuel in a pure form. Fast reactors use a mixture of uranium and fissile ^{239}Pu as primary fuel. The fast neutrons that are created during the fission of ^{239}Pu are used to transmute ^{238}U into ^{239}Pu.

2.2.3 Reactor technologies

This section gives an overview of the different families of reactor designs. A graphical representation can be seen in figure 2.9.

Thermal reactors

Thermal reactors all sustain a nuclear chain reaction by splitting fissile isotopes with slow neutrons. Therefore, all thermal reactors need to use a *moderator* to slow down the neutrons that are generated during the fission process. The type of moderator that is employed can be used as a criteria for categorizing different types of reactor designs:

Light Water Reactors: These reactors use light – 'ordinary' – water as a moderator. Usually the water is used as a coolant as well. Members of this reactor family can be further distinguished by the design of the coolant circulation:

- *Pressurized Water Reactors* (PWR)
- *Boiling Water Reactors* (BWR)

Heavy Water Reactors: These reactors use heavy water (deuterium dioxide, D_2O) as a moderator. Heavy water is less likely to absorb neutrons than light water which

[14] The nuclei do not need to be very close to each other to achieve a state where the chain reaction sustains itself.

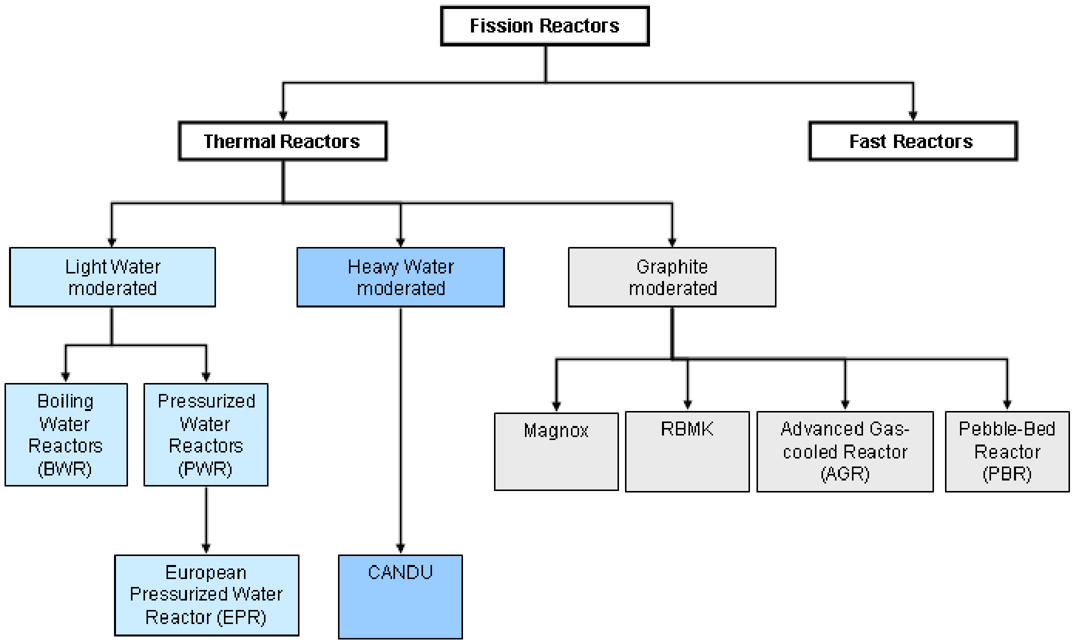


Figure 2.9: Overview of fission reactor designs.

makes it possible to sustain a chain reaction without enriching the fuel. This is a considerable advantage of this reactor family which is partly compensated by the high costs of heavy water. The most common Heavy Water reactor is the *CANDU reactor* which is mainly used in Canada.

Graphite Moderated Reactors: Graphite moderated reactors usually use a gaseous coolant, like helium, nitrogen or carbon dioxide. If the gas can be heated up high enough to drive a turbine directly the very complex steam management system can be eliminated. This facilitates the reactor design and increases the efficiency. The most common reactor types that use graphite as a moderator are:

- *Magnox Reactors* A now obsolete british design.
- *Advanced Gas-cooled Reactors (AGR)* The sucessor of the Magnox reactors.
- *Pebble-bed Reactors (PBR)* In these reactors the fuel is manufactured in tennis ball sized spheres that are coated with graphite. A reactor of this type is presently being built in South Africa.

Fast reactors

These reactors use fast neutrons to sustain a nuclear chain reaction. Therefore, they do not use any kind of moderator which would slow down the neutrons.

Fast reactors can be designed in such a way that a part of the fast neutrons are used to transmute fertile material into fissile material, e.g. to transmute ^{238}U to ^{239}Pu by neutron absorption. A so-called *breeder reactor* is a reactor that produces more fissile material than it consumes. To achieve this, fertile material is packed into *breeder blankets* that surround the reactor core and catch neutrons which leave the core. Reprocessing of the breeder blankets is necessary to extract the fissile material that has been generated.

In fast reactors a coolant is needed that does not slow down (moderate) neutrons. In most reactor designs molten sodium is used as a coolant. This poses a security risk as liquid sodium ignites when it comes into contact with water.

Due to their ability to breed fissile material from the abundant ^{238}U isotope, the wide-spread use of fast reactors would enlarge the nuclear resource base significantly. Supporters claim that this option would become very valuable once the uranium resource base that is available for thermal reactors becomes scarce.

Critics, on the other hand, point out that fast reactors are flawed with uncontrollable security risks and proliferation risks reagarding reactor operation and the necessary re-processing and transportation of large amounts of fuel with high plutonium content.

The operation experience with fast reactors on a commercial scale is fairly small compared to the wide-spread use of thermal reactors, although several fast reactors have been constructed and operated in the US, France, Russia and Japan. However, as of 2006, all existing plants exept for the Beloyarsk reactor in Russia were closed down due to incidents or public opposition.

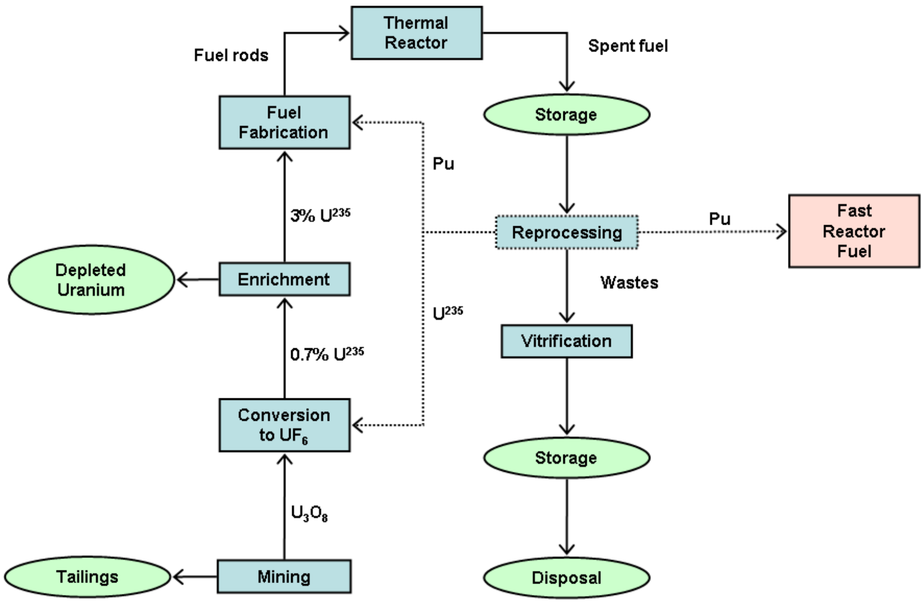


Figure 2.10: Overview of the nuclear fuel chain for thermal reactors. It shows two possibilities of using Plutonium (Pu) that is gained by reprocessing: It can be recycled into fresh thermal reactor fuel (mixed oxide fuel, MOX) or used as a basis for fast reactor fuel. The MOX option is not used in this study.

2.2.4 The nuclear fuel cycle

This section gives an overview of the different stages of the nuclear fuel cycle [15].

A graphical representation of the fuel cycle of thermal reactors can be seen in figure 2.10. An overview of the integration of fast reactors into this scheme is given in figure 2.13 and will be discussed there. I will assume that Uranium is used as a primary resource for fuel generation. The use of Thorium as a fuel basis is not discussed in this study.

Mining

Natural uranium resources mostly occur in the form of *Uraninite*, a mineral that contains, among other components, *uranium dioxide* (UO_2). In most cases uranium ore is extracted from the ground via *open pit mining* or *underground mining*. The extracted ore is crushed to a fine powder and processed with concentrated acidic or peroxide solutions to leach out the uranium content. The resulting solution is then filtered and dried. The product is a coarse, yellow powder that contains 70 to 90 % *uranium octaoxide* (U_3O_8) and is generally referred to as *Yellow cake*. It is insoluble in water and suited for long-term storage. U_3O_8 is the form in which unenriched uranium is usually traded on national and international markets.

As of 2004, 20 % of worldwide uranium was extracted by *in-situ leaching (ISL)*. This process combines the two steps of extracting the ore and leaching out the uranium content by injecting chemical solutions directly into the underground deposit. After a residence time of 3 to 25 years the uranium-rich solution is extracted from the ground.

Conversion and Enrichment

Natural uranium consists of the two isotopes ^{238}U and ^{235}U, with a mass content of 99.3 % and 0.7 %, respectively. Only ^{235}U is fissile (suitable for sustaining a chain reaction in thermal reactors). Therefore, for most thermal reactor designs it is necessary to increase the concentration of ^{235}U in the fuel. The various *enrichment* methods require uranium to be converted into a gaseous compound. This is achieved by the *conversion* of U_3O_8 to *uranium hexafluoride* (UF_6) via several chemical processes. UF_6 is solid at ambient temperatures but can be easily vapourized (boiling point 56 °C. The two most widely used enrichment methods are:

Gaseous diffusion: This process is based on pressing the UF_6 through a semipermeable membrane that has a different permeability with respect to the two uranium isotopes that need to be separated. The gaseous diffusion process has played an important role in the history of nuclear energy but is now slowly substituted by the centrifugation process. The main reason for this is that the process is very en-

[15] Critics of nuclear energy argue that the term *chain* should be used rather than *cycle* to emphasize that a continuous recycling of spent nuclear fuel without generating significant amounts of waste products is not possible. This is especially true for the exclusive use of thermal reactors as it is practised today. However, if the option of using fast reactors is taken into account, a much greater amount of recycling is possible and necessary (although waste products are produced as well). Because the interaction of *both* reactor designs are subject to this study, the term *nuclear fuel cycle* will be used.

ergy intensive, mainly due to compressing, and cooling requirements between the different diffusion stages.

Gas centrifuge process: This process takes advantage of the mass difference between ^{235}U and ^{238}U. The UF_6 gas is put into circular movement which causes the atoms of different mass to dislocate. The centrifuge enrichment process consumes considerably less energy than the gaseous diffusion method, but it still is a very cost-intensive step of the nuclear fuel chain.

Both processes share the feature that many separation steps need to be performed sequentially to increase the grade of separation. For the production of thermal reactor fuel the content of ^{235}U is usually increased to 3 - 5 %. Higher concentrations increase the number of separation stages, but they reduce the fuel change intervals during reactor operation. This increases the overall availability of the reactor which is a considerable cost factor.

A byproduct of the enrichment process is *depleted uranium* with an average ^{235}U content of 0.2 - 0.4 %. Depleted uranium is produced in great quantities which creates a considerable storage problem. It is usually stored in the form of UF_6 which - in case of leakage - evaporates into the atmoshere and builds toxic fluoride compounds.

Fuel fabrication

The enriched uranium is processed in a way that it can be applied as fuel for a nuclear reactor. Inside the reactor, the fuel is exposed to enormous physical strains like high temperatures, high levels of radiation (which increase the porosity of the ceramic matrix) and the creation of gaseous fission products. In most cases the uranium is converted to small pellets made of metallic or ceramic uranium oxide. These pellets are packed in tubes made of Zircaloy, a zirconium alloy that is particularily good at not absorbing thermal neutrons. A certain number of these fuel rods are usually bundled together to form fuel elements, which are transported to the reactor sites.

Reactor operation

During the operation of the reactor the constitution of the reactor fuel changes. Fissile elements like ^{235}U are hit by neutrons and fissioned. This process decreases the concentration of ^{235}U and increases the concentration of *fission products* (elements with a lower mass index than uranium). On the other hand, some elements absorb neutrons and form elements with a greater mass index than uranium, the so-called *transuranium elements*. The most prevalent ones are americium (Am), curium (Cu), neptunium (Np) and various isotopes of plutonium (^{238}Pu, ^{239}Pu, ^{241}Pu). ^{239}Pu is fissile, and the fissioning of ^{239}Pu contributes a considerable part of the energy that is produced in thermal reactors. Fission products and transuranium elements are the main source of radioactivity in spent nuclear fuel.

It is impossible to fission all fissile elements that are present in a batch of fuel. During operation, the decreasing concentration of fissile elements and increasing concentration of fission products and transuranium elements reach a point where it is impossible to sustain a nuclear chain reaction. At this point the fuel is considered as *spent* or *irradiated* and needs to be replaced.

Classification of nuclear waste

Before I describe the stages of the back end part of the fuel cycle I will comment on the classification of different types of radioactive waste. Classification can be done via various parameters:

- origin
- physical state (liquid, solid, gaseous)
- level of radioactivity
- decay time
- level of heat generation

A standardized international classification system for radioactive waste does not exist. Several countries that use nuclear energy have developed classification schemes that can be applied to their national authorities regulations.

The classification system that was applied for this study uses three waste categories[16]:

- Low Level Waste (LLW) has a half-life time that is sufficiently low to dispose of it in *engineered shallow land disposal* sites. The most common boundary that is used to distinguish between LLW and ILW is a half-life time of 30 years.
- Intermediate Level Waste (ILW) has a longer half-life time or a greater concentration of radioactive components and hence requires disposal in deep geological repositories.
- High Level Waste (HLW) The distinction between ILW and HLW is mainly by heat generation and source of origin. HLW always needs to be stored before disposal in a deep geological repository. It contains spent reactor fuel, highly radioactive waste from fuel reprocessing, and other waste types with a similar radioactive content.

Waste conditioning and disposal

The composition of spent fuel varies considerably depending on the reactor design, reactor operation, and the composition of the fresh fuel. The following components are important:

- About 95 % of the spent fuel consists of the non-fissile ^{238}U.
- About 0.50 % consists of the remaining fissile ^{235}U.
- About 1 % of the mass is ^{239}Pu and ^{240}Pu.

[16] For details refer to NEA (1994).

- The remaining 3.5 % are made up of a variety of fission products and transuranium elements.

After removal from the reactor core, the irradiated fuel is stored for a period of ca. 15-30 years on the reactor site to allow short-lived radionuclides to decay. During this period the fuel generates great amounts of heat which requires sophisticated cooling systems.

There are basically two options on how spent fuel can be treated: In can either be conditioned and deposited directly, or it can be reprocessed. Both options will be discussed.

Reprocessing

Reprocessing describes the process of chemically and/or physically separating irradiated nuclear fuel into different product streams. Irradiated fuel contains significant amounts of plutonium and ^{235}U that can – if being separated via reprocessing – be reintegrated into the production of fresh nuclear fuel, either for fast reactors or – in the form of mixed oxide fuel – for thermal reactors.

The predominant reprocessing method is the PUREX process which is used at the two biggest reprocessing plants worldwide, Sellafield (UK) and La Hague (France). The spent fuel elements are cut into small pieces and dissolved in nictric acid. An organic solvent is added to recover uranium and plutonium while the fission products remain in the aqueous nitric phase. Further process steps enable the separation of uranium and plutonium.

Reprocessing allows to separate plutonium in a form that can be used to fabricate nuclear weapons and therefore increases the risk of proliferation. For this reason, reprocessing of nuclear waste was banned in the US by President Carter in 1977.

Mixed oxide (MOX) fuel MOX fuel is a blend of plutonium and uranium (natural or reprocessed) that can be used (to a certain extent) in thermal reactors instead of enriched natural uranium. It provides a way to recycle the plutonium and uranium that is separated from spent fuel via reprocessing.

However, this option has its technical limitations. MOX fuel behaves similar, but not exactly like fuel that is based on enriched natural uranium. Traces of transuranium elements and fission products change the behaviour of the reactor core during operation. It is common practice not to operate thermal reactors fully on MOX fuel, but to add a certain percentage of MOX fuel to the conventional fuel based on natural enriched uranium. Additionally, the operation of reprocessing plants is very costly, and during the process large amounts of low level radioactive waste is generated. There has been considerable public opposition against the reprocessing plants in La Hague and Sellafield. The MOX fuel option might become interesting from an economical point of view when uranium resources become scarce and a more efficient use of the prevailing resources is necessary. At best, using the MOX option reduces the demand for natural uranium by 30 % (MIT, 2003). The same reference comes to the conclusion that the use of MOX fuel is not viable under economical aspects. It's use will not be considered in this study.

Direct disposal

If the decision is made not to recycle any components of the spent fuel, it can be disposed directly without reprocessing. The usual process is to cast the fuel rods into borosilicate glass and store them in deep geological repositories (after an intermediate storage period for cooling down).

As of today there exists no operational repository for the terminal storage of spent nuclear fuel elements, although many countries are working on projects to that effect.

2.3 Non-nuclear technologies

In this section I will give a brief technological description of the transformation technologies that are used in the energy system model. Technolgies that are related to the use of nuclear energy are discussed separately in sections 2.2.3, 2.2.4 and 2.4.2.

2.3.1 Fossil energy sources

Natural gas turbine (ngt)

This is the most straightforward way to use natural gas as an energy source for generating electricity: A (compressed) mixture of gas and air is burned in a combustion chamber. The exhaust gases are used to drive a gas turbine directly. The turbine is connected to a generator which produces electricity. Because of their simple design, gas turbines have very low investment and operation costs. Furthermore, they have a small footprint and can be activated and shutdown quickly. The major disadvantage of gas turbines is that the thermal energy of the exhaust gases is not used which leads to a low efficiency.

Natural gas combined cycle powerplant (ngcc)

The NGCC technology is an extension of the gas turbine which aims at increasing the efficiency of the system. After leaving the gas turbine the hot exhaust gases pass a heat exchanger where water is vaporized to power a steam turbine. Modern NGCC power plants achieve efficiency factors of up to 58 % (BMWA, 2003). Because of increasing fuel costs and technological advances it is very likely that in future investments the combined cycle technology will supersede the simple gas turbine process (IEA/OECD, 2003).

Pulverized coal power plant (pc)

In modern coal-fired power plants the coal is ground into a fine powder which is injected into the combustion chamber and burned in a *fluidised-bed process*. Hard coal or lignite can be used as fuel. Modern PC power plants usually achieve efficiency factors of up to 47 % (BMWA, 2003).

Carbon Capture and Sequestration (CCS)

A detailed introduction to the technology of carbon capturing is given in IPCC (2005). It is technically possible to capture carbon from all combustion engines that use carbohydrates as an energy source, but due to the considerable technological effort it is only economically viable for large point emitters. The capturing process leads to a significant decrease in overall efficiency which results in an increase of fuel consumption per kWh[17]. For this study, the use of CCS has been implemented for gas combined cycle and pulverized coal power plants.

2.3.2 Renewable energy sources

Wind turbine

Wind turbines use the kinetic energy of wind to power a generator which in turn produces energy. Of all non-traditional renewable energy sources this technology has the largest market share (1.5 % of global electricity production (IEA, 2005a))and the lowest electricity generation costs. For this study, only on-shore wind turbines have been considered.

Photovoltaic power plant

The parameters that were used for this study represent grid-connected, centralized electricity generation via the use of silicium-based photovoltaic modules. However, assumptions about the future development of this technology are just as important as the initial parameters. Due to the large timeframe of the model and the substantial technological change that is expected to take place in this sector, the parametrization needs to be regarded as somewhat generic.

Hydropower

Hydropower falls into the category of traditional renewable energy. As of today, it accounts for a substantial share of global electricity production (15.9 % (IEA, 2005a)). For this study only large scale hydropower was taken into account.

2.4 Structure of the energy system

2.4.1 Overall structure

Figure 2.11 shows the structure of the energy system that is used in this study. It covers the electricity sector – there exists an external demand for one single final energy type electricity.

Final energy electricity is produced from secondary energy electricity via a generic transportation and delivery technology that represents the electrical grid.

[17] IPCC (2005) mentions an increase in fuel consumption of 14 – 40 % compared to power plants without CCS.

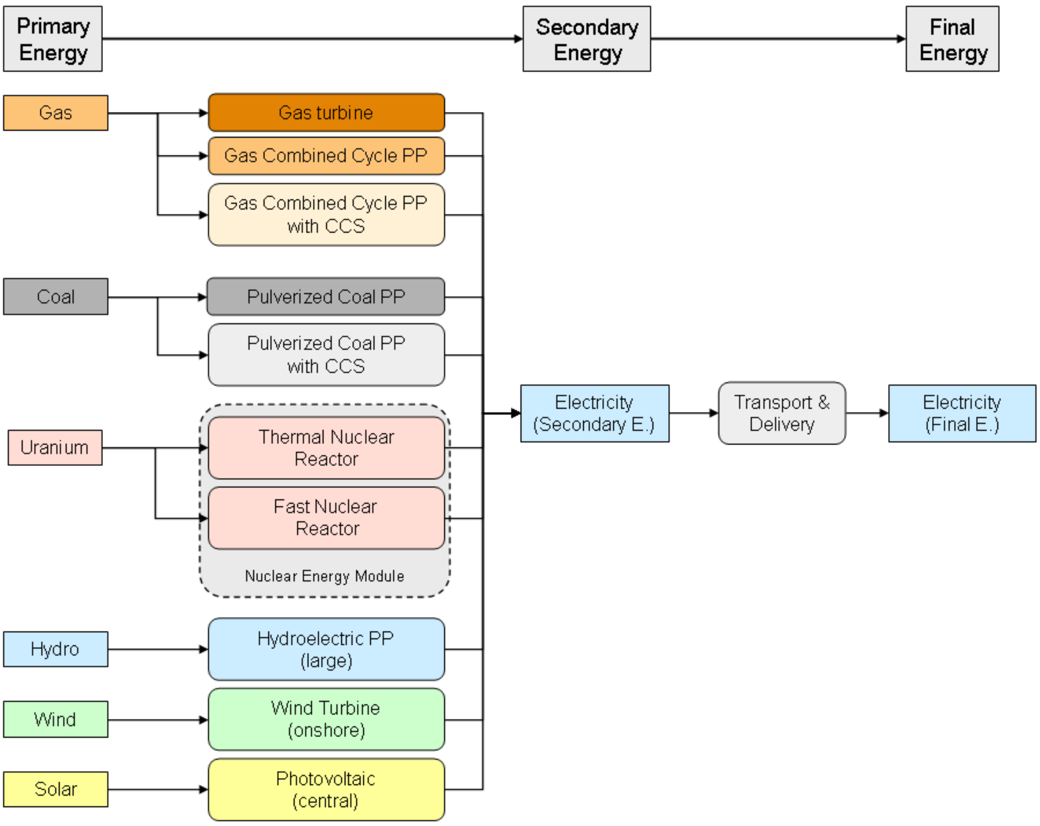


Figure 2.11: Structure of the energy system. Details of the nuclear power sector are shown in figure 2.13.

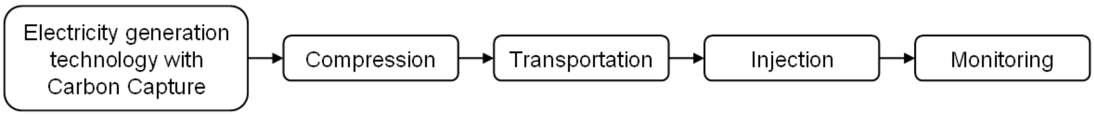


Figure 2.12: Transformation chain for captured CO_2.

Secondary energy electricity is produced by a set of generation technologies. The non-nuclear technologies have been described in section 2.3. Electricity generation by nuclear reactors is embedded into an nuclear fuel cycle moduel that will be discussed separately in section 2.4.2. The use of nuclear reactors generates nuclear waste as a side product.

In the model there exist three different exhaustible primary energy resources – natural gas, coal and uranium – and three renewable energy sources (hydro, wind and solar energy).

Not shown is the generation of emissions (CO_2) and the capturing of CO_2. CO_2 emissions are generated by all technologies that use coal or gas as an energy source. Captured CO_2 is produced by the two CCS technologies and subsequently transported via a chain of technologies into repositories (see figure 2.12).

2.4.2 The representation of nuclear energy

Figure 2.13 shows how nuclear energy is represented in the energy system model. The primary energy resource, uranium ore, is shown on the left hand side of the diagram. The electricity that is produced and the different classes of nuclear waste are shown on the right hand side. The fuel cycles associated with thermal and fast reactors are situated in the upper and lower half, respectively. In the center, the interconnections between the two fuel cycles are shown.

Reactor technologies

Two different reactor types are represented in the model. Both of them produce secondary energy electricity as main output and spent fuel as couple products.

Thermal nuclear reactor (TNR) This technology represents the majority of the reactors that is in operation as of today, and most likely this reactor design will be applicable to many thermal reactors that will be built during the next decades.

Fast Nuclear Reactor (FNR) This technology represents the fast reactor option. As of today, almost no fast breeder reactors are in operation, although this technology might become an option for future investment decisions.

Front end of the fuel cycle

Primary energy uranium enters the process chain in the physical form of uranium octaoxide (U_3O_8). All extraction and transformation processes that are necessary to produce

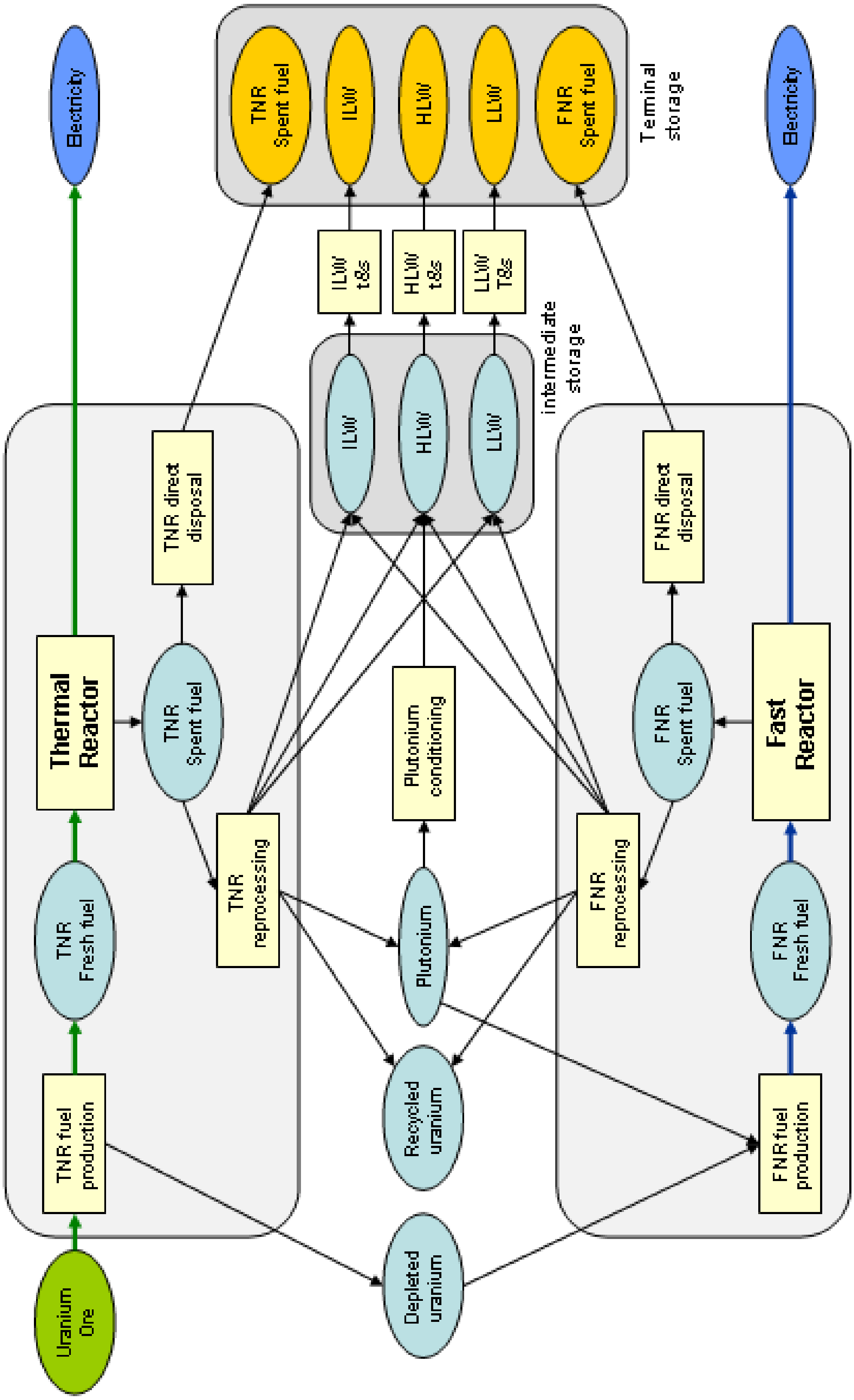


Figure 2.13: Representation of nuclear energy in the energy system model. TNR: Thermal nuclear reactor, FNR: Fast nuclear reactor. HLW, ILW, LLW: High, intermediate and low level waste.

this substance (mining, milling, conversion) are not implemented in the model structure. Any investment and energy requirements associated with these processes are accounted for by assuming a specific fuel cost for each unit of (U_3O_8) that is consumed[18].

The process steps that are necessary to transform (U_3O_8) into fresh TNR fuel elements are aggregated to one single technology (*TNR fuel production*). This includes the conversion of (U_3O_8) to UF_6, the enrichment process, the conversion to metallic or ceramic compounds, and the production of the fuel elements itself. As a couple product this process generates *depleted uranium*.

Fast reactors are fueled with a mixture of plutonium and uranium[19]. Plutonium is gained by reprocessing of spent fuel of thermal or fast reactors.

Back end of the fuel cycle

For each reactor type there are two options to dispose of the spent fuel elements: *direct disposal* and *reprocessing*. As the composition of thermal and fast reactor spent fuel is considerably different there are different technologies for each of the two fuel types. The direct disposal technologies represent the conditioning of the complete fuel elements, which includes volume reduction, vitrification, and encapsulation in suitable containers. They only have one single output which is *High Level Waste (HLW)*. The reprocessing technologies have various output streams: plutonium, recycled uranium, and waste of all three categories (*HLW*, *ILW* and *LLW*).

Plutonium can be recyled into fast reactor fuel. Excess plutonium is considered as a waste product and is converted to High Level Waste by a *Plutonium conditioning* technology.

The waste products that are generated by the direct disposal, reprocessing and plutonium conditioning technologies are considered to be in the status of *intermediate storage* (which has a maximum storage capacity). Surplus waste needs to be transferred to a terminal storage facility by a *transportation and storage* technology. As the handling and the disposal options of the three waste categories differ considerably each waste category has its own transportation and storage technology.

The recycling of plutonium and uranium into the thermal reactor fuel cycle via the production of MOX fuel is not regarded in the model. Nevertheless, reprocessing of thermal reactor spent fuel is necessary to generate plutonium which is essential for the production of fast reactor fuel - at least until there are enough fast reactors to breed their own plutonium.

2.4.3 Limitations and scope

Due to the limited scope of a diploma thesis, some technological options and model features were deliberately not used in the model. They are described in this section.

[18]The representation of extraction processes is not yet implemented in genEris. This is planned for future projects.

[19]Uranium for fast reactor fuel production is taken from the 'depleted uranium' stock. It would be technically possible to use natural ore or recycled uranium for this purpose. These pathways have not been included in the model because the stock of depleted uranium is too high to become a binding constraint.

The model was designed on the basis of an existing, much larger, model that covered all key sectors of the electricity system (electricity, heating and transportation). The electricity sector of the original model was separated, simplified, and subsequently extended with the modifications that were discussed in section 2.1.3.

Resources that are not represented

Oil In 2003, oil accounted for 6 % of global electricity production (IEA, 2005a). But as oil prices are expected to rise significantly and the substitution of oil by other energy sources is much more difficult in other sectors (notably the transportation sector) it can be expected that oil will play a very minor role in future electricity generation. Because of this, the use of oil as an energy resource was excluded from the model.

Biomass and geothermal energy These two resources were not integrated because of the limited scope of the study.

Different types of coal For the same reason, no distinction between hard coal and lignite has been made.

Only one technology per resource

To keep the model as straightforward as possible, more than one technology that are based on the same primary energy resource were only implemented if these technologies could be distinguished by unique features[20]. Technologies that can be considered as a mere improvement of or a similar alternative to an existing one were not implemented[21]. Due to this principle integrated coal gasification and solarthermal power plants were not implemented. It is also the reason why only one generic type of thermal nuclear reactors was used, although a variety of different concepts are on the market, and why the recycling of plutonium into the thermal reactor fuel chain (by using mixed-oxide fuel) was not implemented. It was regarded as sufficient to implement the fast reactor as one technological option to increase the efficiency of the use of uranium.

2.5 Parameters

This section describes the parameters that were used. In the text the names of technologies and energy types are written out whereever it is possible. In most of the tables, abbreviations have been used. A list of abbreviations can be found in tables A.5 and A.6. Table A.8 contains a description of the units that were used.

[20] For example, fast and nuclear reactors use the same resource base (uranium), but they do so in a very different way, and pulverized coal power plants with carbon capture will behave different than pulverized coal powerplants without capture under an emission constraint.

[21] The implementation of gas turbines can be considered as a deviation from this rule. This was done because gas turbines play an important role in electricity generation today. The insights gained from doing so were not very surprising, as will be discussed in section 3.1.

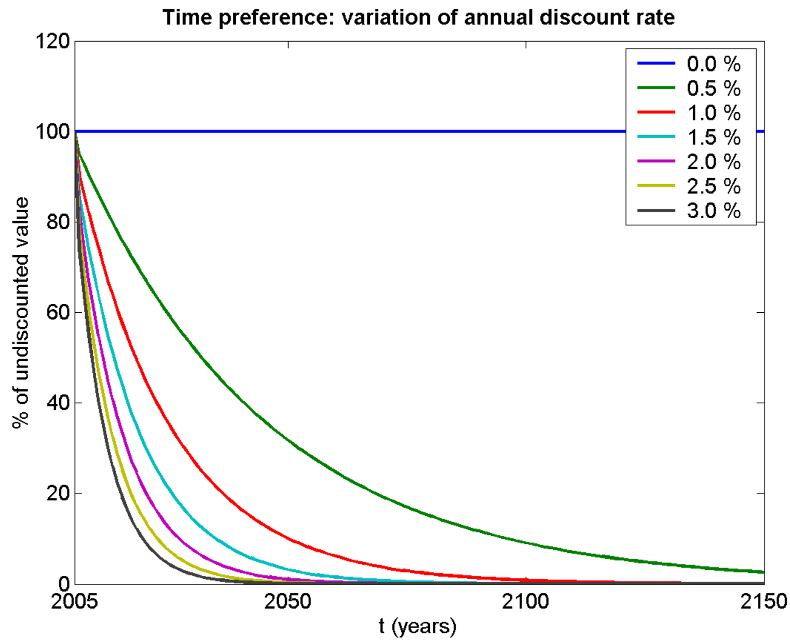


Figure 2.14: This figure illustrates how different annual discount rates affect the net present value of investments that occur in the future.

2.5.1 Time horizon and discount rate

The time horizon of the model is 150 years (2005 – 2150). Only the results for the first 100 years (2005 – 2100) will be evaluated to eliminate end effects[22] The model was evaluated at discrete 5-year timesteps.

It is common practise in economic studies to discount payments that occur in the future. This generates a *time preference* where costly investments tend to be delayed as long as possible. However, if large time horizons are examined, high discounting rates can lead to a situation where the net present value of investments that occur late is so small that they can be neglected. Figure 2.14 shows the effect of different annual discount rates on the net present value of investments over a time range of 150 years.

In this study an annual discount rate of 2 % has been chosen.

2.5.2 Demand scenarios

The assumptions regarding the development of final energy demand have a great impact on the structure of the energy system. At the same time it is quite difficult to develop consistent demand scenarios, as demand is affected by many different driving forces whose development is difficult to predict as well.

Figure 2.15 shows the two demand scenarios that are used in this study. For both scenarios the annual growth rate is constant until 2075 (2 % and 2.5 %, respectively) and declines at a constant rate close to zero growth at the end of the time horizon. The

[22] For example, technologies with high investment costs will not be used at the end of the time horizon if their lifetime exceeds the time limit of the model.

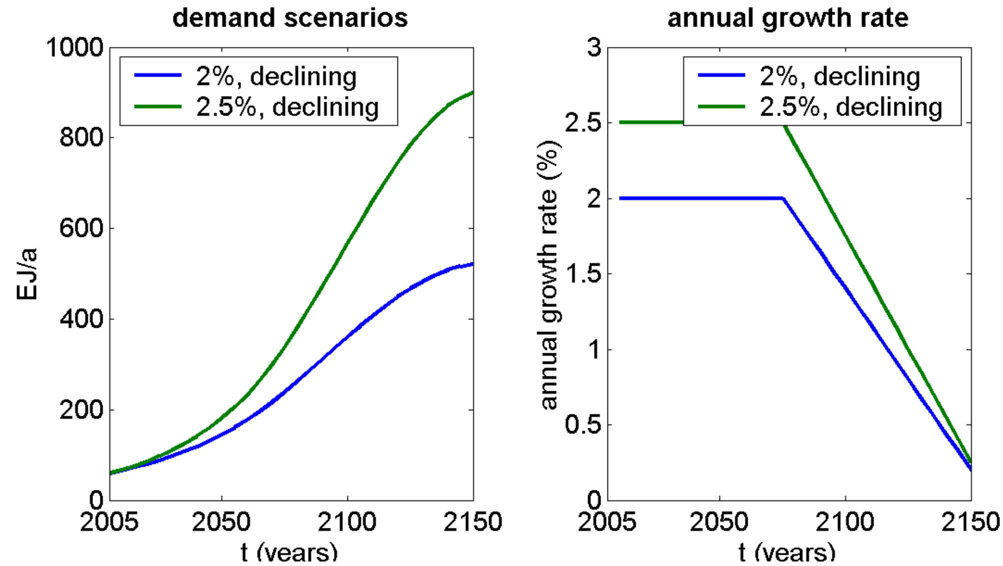


Figure 2.15: Demand scenarios that are used for this study. The left graph shows the annual demand, the right graph shows the annual growth rate.

high demand scenario is comparable with an SRES A1 scenario (IPCC (2001b)), the low scenario fits in quite well with the B1 / B2 scenarios. Note the different time horizons in the SRES scenarios (1990 – 2100) and this study (2005 – 2150).

Both scenarios share the same initial demand of 58.9 EJ/a in 2005 (IEA (2005a))[23].

2.5.3 Emission scenarios

Regarding emission constraints, two different scenarios have been used in this study. The *Business as Usual (BAU)* scenario does not impose any emission constraint. For the *policy scenario* a timepath was defined that imposes maximum annual CO_2 emissions for each timestep. This emission pathway was calculated by the model MIND (Edenhofer u. a., 2005). MIND is an integrated assessment model that couples a energy system model of medium complexity, a macroeconomic growth model and a carbon cycle model. In MIND, the chosen emission pathway corresponds to a stabilization of atmospheric CO_2 emissions at 450 ppm. The emission pathway needs to be adapted because MIND models the complete energy sector and not just the electricity sector as it is done in this study. It is assumed that the electricty sector contributes 25 % of total anthropogenic $\mathrm{CO_2}$ emissions, and that this share remains constant over the complete time horizon. The adjusted emission constraint timepath is shown in figure 2.16.

It is important to note that MIND maximizes intertemporal welfare, while genEris minimizes intertemporal energy system costs. This implies that in MIND demand is calculated endogenously, while in genEris this parameter is set exogeneously. This is an important difference, as the emission pathway derived from MIND does not necessarily fit well with the demand scenario imposed on genEris – especially with high fossil fuel prices, genEris does not have the option to decrease electricity demand at the end of the time frame, when the emission constraint becomes fairly restrictive. Using a MIND emission pathway

[23] In further research this value should be revised. The most recent edition of the reference states an annual electricity demand of 62.8 EJ/a.

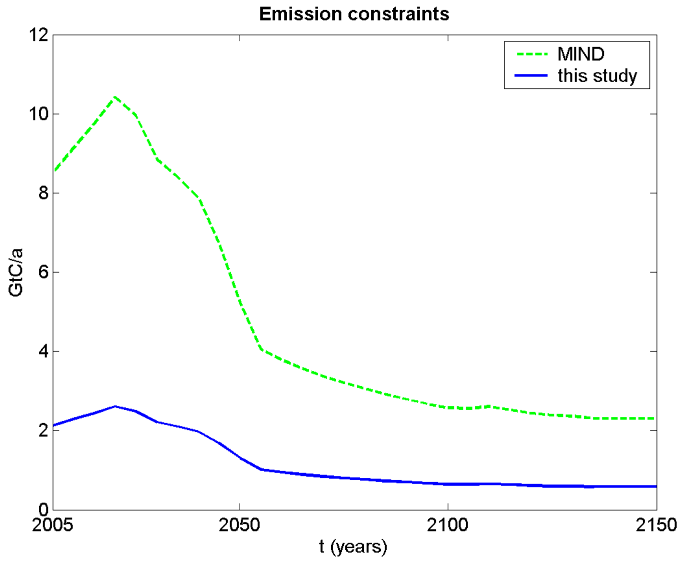


Figure 2.16: Emission constraints for the 450 ppm stabilization policy scenario.

needs to be seen as a provisionary solution, as after the completion of this study genEris will be coupled with a macroeconomic growth model where demand is determined endogeneously. Because of these plans, designing adequate emission scenarios had a rather low priority.

2.5.4 Resources and potentials

Exhaustible resources

Three exhaustible energy sources are considered in this study: coal, natural gas and uranium. No distinction between hard coal and lignite is made. Oil is not represented at all.

For each energy type, a specific *fuel cost* is defined. This cost is to be paid for each energy unit that is consumed. For coal and gas this cost is defined per energy unit, for uranium per mass of uranium. This is done because the energy that can be produced from a certain mass of uranium depends on many factors as reactor technology, mode of reactor operation, fuel cycle variations, grade of enrichment, burnup etc.

As exhaustible resources are consumed, it gets more and more difficult and cost-intensive to produce more of the same energy type. Nordhaus und Boyer (2000) introduced a method to describe specific extraction costs as a function of cumulated resource extraction. This empirical relationship, which will be refered to as 'Rogner curve', is given in equation 2.28. Its graphical representation can be seen in figure 2.17.

$$c(t) = \chi_1 + \chi_2 \left(\frac{X_{cum}(t)}{\chi_3} \right)^{\chi_4} \tag{2.28}$$

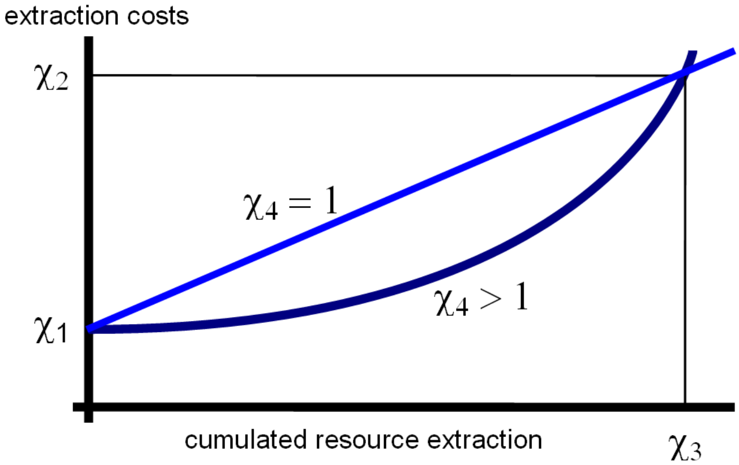


Figure 2.17: Stylized Rogner curve (Nordhaus und Boyer, 2000).

$c(t)$	fuel cost at time t
$X_{cum}(t)$	cumulated extraction at time t
χ_1	initial fuel cost (at time t_0)
χ_2	difference between initial and end cost
χ_3	total resource base
χ_4	curvature factor

Coal and gas Figure 2.18 shows the historical price development for coal and gas as reported in the BP Statistical Review 2006 (BP, 2006) [24]. While coal prices remain relatively stable there has been a sharp increase in gas prices during the last five years.

Table 2.2 lists the Rogner parameters for various resource scenarios that were used. For this study the initial fuel costs for 2005 (χ_1) have been set to 2.5 $\$/GJ$ for coal and 5.0 $\$/GJ$ for natural gas. The total resource base equals two times the known reserves that are stated in (BP, 2006). An increase of extraction costs (χ_2) up to 300 % of the actual costs is assumed.

Not only the future increase of fuel costs (represented by the Rogner curve parameter χ_2) but also the present costs (χ_1) are subject to significant uncertainties. This is illustrated by figure 2.19 which represents the oil price projections for the next 30 years by the International Energy Outlook 2005 and 2006 (EIA, 2006)[25]. The projections in the two studies, which have been conducted by the same authors in two succeeding years, diverge by more than 30 %. Because of this, both Rogner parameters have been varied in the multi-run experiments that will be presented in section 3.2.

Uranium Every year the Nuclear Energy Association (NEA) publishes an assessment of the global uranium resources and reserves (the so-called *Red Book*). Figure 2.20 shows the figures that are given in the 2003 report (NEA, 2003b). Resources are categorized by

[24] The values have been converted to $\$/GJ$ using the conversion factors that are given in the report. For coal the mean value of the heating values of hard coal and lignite has been used.

[25] The use of oil as an energy source is not included in this study. But as gas prices are (currently) linked to the oil price development, this graphic is presented nonetheless.

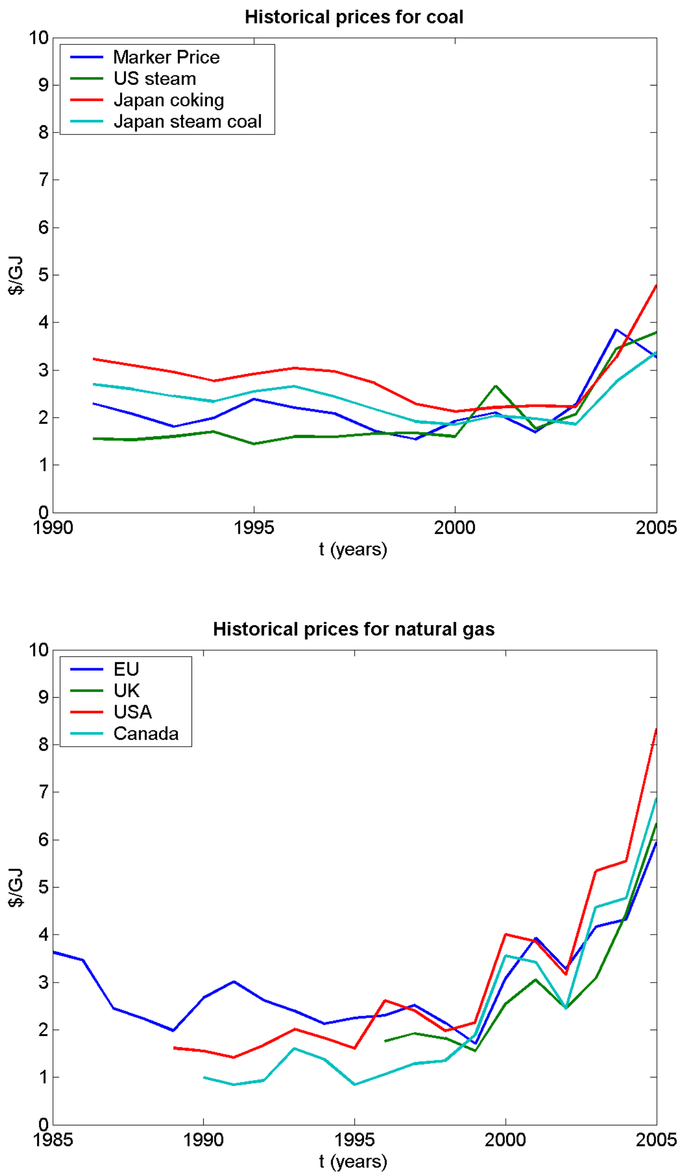


Figure 2.18: Historical prices for coal and gas (BP, 2006).

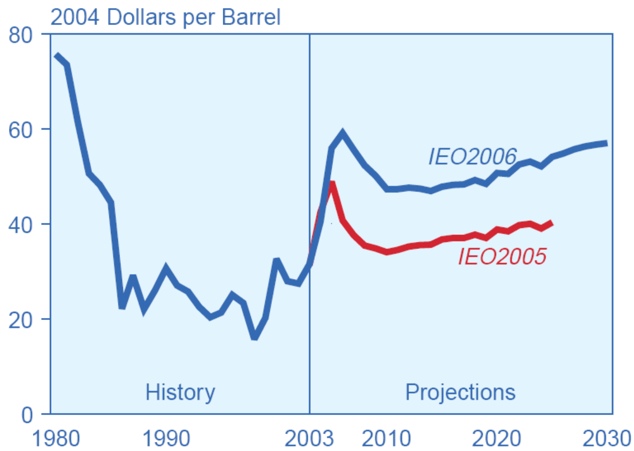


Figure 2.19: Oil price projections according to the International Energy Outlook 2005 and 2006 (EIA, 2006).

Table 2.2: Rogner curve parameters for the determination of exhaustible resource costs. Units: EJ and $/GJ for fossil fuels, MtHM and $/kgHM for uranium (HM for *Heavy Metal*, see appendix for a list of units and abbreviations).

Resource	Scenario	χ_1	χ_2	χ_3	χ_4
Coal	low	1.25	2.50	60000	2.00
	high	2.50	5.00	60000	2.00
Gas	low	2.50	5.00	20000	2.00
	high	5.00	10.00	20000	2.00
Uranium		30.00	300.00	16.6	1.50

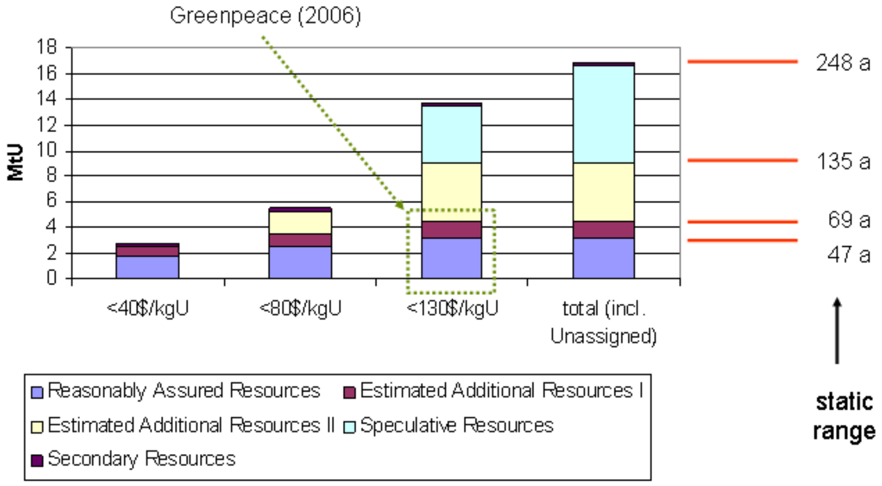


Figure 2.20: Uranium resources based on (NEA (2003b). The four bars represent different extraction cost categories, the colors represent the level of confidence. Secondary resources are also shown – their size is small compared with natural ore resources. The green rectangle marks the resource base that was considered in Greenpeace (2006)). On the right hand side the static range is shown, based on 2003 consumption.

the expected specific extraction costs as well as by the amount of uncertainty regarding the assumptions about their size and cost[26]. If all categories are taken into account, the total resource base amounts to 16.7 MtU which is equivalent to a static range of 250 years. However, there exists a considerable amount of uncertainty about the true size of the 'speculative' resources. In 2006, Greenpeace examined the global uranium resources (Greenpeace, 2006) and decided only to consider the NEA categories *Reasonably Assured Resources (RAR)* and *Estimated Additional Resources I (EAR I)* with estimated extraction costs of < 130 $/kgHM. This fraction only amounts to 4.3 MtU which equals a static range of 69 years. Figure 2.20 also shows the size of secondary uranium sources. It shows that, although today these resources cover a significant share of uranium demand, future demand will have to rely on primary sources of uranium (Greenpeace, 2006).

For this study the cost and size assumptions for primary energy uranium have been represented as a Rogner curve as well. The parameters have been chosen to represent the data from NEA (2003b). *All* resource grades that have been defined by NEA (2003b) have been taken into account. Figure 2.21 shows the respective Rogner curve. Table 2.2 shows the respective Rogner curve parameters.

[26]The figures do not include unconventional uranium sources like seawater or granite rock.

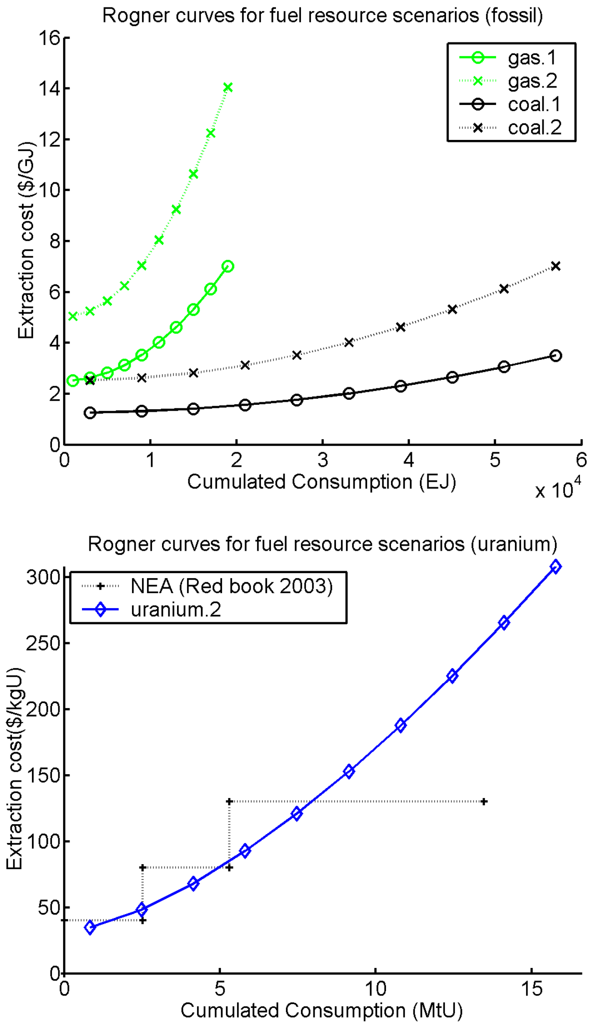


Figure 2.21: Rogner curves for different resource scenarios that were used for this study. The steps in the uranium price figure represents the cost assumptions given in NEA (2003b).

Renewable energy sources

Three renewable energy sources are represented in this study: Wind energy, solar energy and hydropower.

The available *resources* of renewables energy sources are not diminished by using them. But for each energy source there exists a limit on the *potential* as to how much energy can be generated at a certain time. There exist a varieties of studies on the potential of renewable sources (e.g. UNDP (2000), Hoogwijk (2004) and Archer und Jacobson (2005)). It is important to consider which contraints are taken into account when assessing these potentials. The following classification of potentials is widely used (eg. (Hoogwijk, 2004)):

- The *theoretical* or *physical* potential is the maximum limit of the primary resource. In the example of solar energy, this would be the total solar radiation that reaches the earth's surface.
- The *geographical* potential defines the part of the theoretical potential that occurs in locations it can be used under practical considerations - for example, the surface of the oceans, high montains, urban and agricultural areas as well as nature reserves cannot (or only to a certain amount) be used to generate solar electricity. This definition obviously leaves room for interpretation, as solar panels can be mounted on roofs, and wind turbines can be situated on land surfaces that are simultaneously used for agricultural purposes.
- The *technical* potential takes into account the energy losses that are associated with the transformation of primary to secondary energy, and the technical limitations on how much secondary energy can be produced. This is affected by factors like the rated power of a wind turbine and the minimum distance between two adjacent wind turbines.
- The *economical* potential is the total amount of the technical potential that can be used in a way that is economically competitive with other available sources of energy.
- The *implementation* potential is the share of the technical potential that is implemented in the energy system. It can differ from the economical potential due to policy incentives or restrictions, market imperfections, social preferences, among others.

The input that is needed for genEris-type energy system models is information about the *geographical* or the *technical* potential[27]. The assessment of the economical potential form part of the result of the model calculations and vary with the assumptions that are made concerning technological and economical model parameters.

Table 2.3 gives an overview of the parameters that characterize renewable energy sources that were used in this study. The maximum potential data is based on the information

[27] The choice between geographical and technical potential affects the formulation of the potential constraint of the model where technological restriction (like efficiency and availability factors) can be included or not.

Table 2.3: Potential constraints and availability factors for renewable energy sources. The resource availability factors are given for the highest and the lowest grade ($\nu_r(max)$ and $\nu_r(min)$, respectively). 'spv' stands for *Solar Photovoltaic* – see appendix for a complete list of abbreviations.

	Max. electricity production π_T ((EJ/a))		Availability factor	
Resource	UNDP (2000)	This study	$\nu_r(max)$ (-)	$\nu_r(min)$ (-)
hydro	51.5	51.5	0.500	0.200
spv [a]	189 – 5980	1500	0.250	0.070
wind [b]	67.3	40.4	0.309	0.004

[a] The minimum and maximum reflect different assumptions on annual clear sky irradiance, annual average sky clearance, and available land area.

[b] This value includes a constraint on maximum land use of 4 %.

provided by UNDP (2000). This reference states the technical potential, i.e. the amount of electricity that can be produced by using a certain energy source.

For this study, the total potential for each energy resource has been divided into equally sized grades (seven for wind turbines and photovoltaic, five four hydropower). The 'quality' of each grade is determined by the availability factor that is associated with it.

The availability factors ν_r for wind energy have been taken from Archer und Jacobson (2005). The values stated in the reference have been scaled down by a factor of 0.5 [28]. The availability factors for photovoltaic and hydropower are based on personal estimates and need to be refined for further research. IEA (2005b) states an average availability factor for large hydroelectric installations of 0.45.

In genEris all renewable potentials are divided into grades that are distinguished by different availability factors that affect the ratio between installed capacity and produced electritiy per time.

2.5.5 Parameters of nuclear energy technologies

Material flow and energy data

Table 2.4 shows the material flow data for the nuclear fuel cylce technologies. For the nuclear waste transportation and storage technologies (hlwis2ts, ilwis2ts and llwis2ts) a transformation factor of 1 was used, i.e. the volume of the waste does not change during transportation and storage. The material flows of the front end of the nuclear cycle and the flows of plutonium and uranium that is separated during reprocessing of spent fuel can be determined with a good degree of certainty – but one has to keep in mind that they vary with the burnup factor of the reactors and other aspects of reactor operation. The uncertainty that is associated with the waste flows is much higher – these depend on the choice of reprocessing, containment and disposal technology, and on the choice of

[28] In the reference, an detailed assessment of the global geographical potential of wind energy, graded by average wind speed classes, is given. The scaling has been applied to represent the fact that due to technical restrictions not all wind turbines will be constructed on the globally optimal sites.

waste categories.

For the processes of fuel production and reprocessing (which are very energy intensive) an own consumption of elecricity of 0.1 TWa/MtHM is used. This value is not based on literature[29]. An own consumption greater than zero was chosen just to demonstrate that this model feature is working. The choosen value is quite low (about 1 % and 2 % of the Burnup for fast and thermal reactors, respectively).

Economic data

Table 2.5 shows the choosen economic parameters for technologies of the nuclear fuel cylce[30]. For several technologies, not all the parameters that are supported by genEris (investment costs, fixed and variable O&M costs) have been used. In current literature it is quite common to represent the economics of these technologies by defining a specific cost factor per unit of main output or main input. In the genEris structure this corresponds to the variable o&m costs. In the current parametrization the technologies for fuel production, reprocessing and direct disposal are represented only by this parameter. For the investment costs of these technologies a very low, 'nominal' value has been chosen (a value of zero would cause a division by zero during model performance). The fixed o&m costs are zero for all nuclear fuel cycle technologies, with the exception of the reactor technologies.

For nuclear power the capital costs of the reactor technology itself contributes a major share to the total electricity generation costs. Unfortunately this parameter is associated with a good deal of uncertainty. Several studies considering the economics of nuclear power generation are summarized in Thomas (2006). The stated capital (investment) costs range between 900 and 5400 $/kW (thermal reactors). Data regarding fast reactors are even more uncertain due to the lack of experience and the small number of plants that have actually been operated on a commercial scale. Chakravorty u. a. (2005), in a study that uses a detailed nuclear energy fuel cycle model similar to the one that was developed for this work, uses investment costs for fast reactors of 4500 $/kW. For this study, investment costs of 2500 $/kW and 4500 $/kW have been choosen for thermal and fast reactors, respectively. Due to the high degree of uncertainty, both parameters have been varied during the multi-run experiments that are presented in section 3.2.

Table 2.5 shows the economic parameters of nuclear technologies.

2.5.6 Parameters of non-nuclear technologies

Economic parameters

Table 2.6 shows the economic parameters that have been used for non-nuclear technologies. For all electricity generating technologies, fixed o&m costs of 2 % per year have been assumed.

[29]Usually, own consumption of electricity is included in the operation and maintenance costs, so it is not easy to find this kind of data.

[30]US dollars ($) are used as a monetary unit throughout this study.

Table 2.4: Material flows in the nuclear energy module. Positive and negative values represent production and consumption, respectively. In the model code these parameters are represented by the transformation and own consumption factors (η and ξ.). See appendix for a list of abbreviations and units.

Technology	stream		unit	note
tnrfp	peur[a]	-10.243	MtHM/MtHM	(per mass of fresh fuel)
	depur[a]	9.243	MtHM/MtHM	
	seel	-0.100	TWa/MtHM	
tnr	seel[b]	45.205	TWa/MtHM	(per mass of fresh fuel)
	tnrpr	1.000	MtHM/MtHM	
tnrdd	tnrsfts[c]	2.000	m^3/tHM	(per mass of spent fuel)
tnrrep	puis[d]	0.013	MtHM/MtHM	(per mass of spent fuel)
	recur[d]	0.934	MtHM/MtHM	
	hlwis[e]	0.100	m^3/tHM	
	ilwis[e]	0.882	m^3/tHM	
	llwis[e]	5.883	m^3/tHM	
	seel	-0.100	TWa/MtHM	
fnrfp	depur[f]	-0.760	MtHM/MtHM	(per mass of fresh fuel)
	puis[f]	-0.240	MtHM/MtHM	
	seel	-0.100	TWa/MtHM	
fnr	seel[b]	131.507	TWa/MtHM	(per mass of fresh fuel)
	fnrpr	1.000	MtHM/MtHM	
fnrdd	fnrsfts[c]	2.000	m^3/tHM	(per mass of spent fuel)
fnrrep	puis[f]	0.240	MtHM/MtHM	(per mass of spent fuel)
	recur[f]	0.760	MtHM/MtHM	
	hlwis[e]	0.100	m^3/tHM	
	ilwis[e]	0.882	m^3/tHM	
	llwis[e]	5.883	m^3/tHM	
	seel	-0.100	TWa/MtHM	

[a] Enrichment data has been taken from MIT (2003), assuming ^{235}U concentrations in natural, enriched and deriched uranium of 0.711 %, 4.51 % and 0.3 %, respectively.

[b] Source for the electricity yield data: MIT (2003) (based on burnup of 50 and 120 GWd/tHM and thermal efficiency η of 0.33 and 0.40 for thermal and fast reactors, respectively).

[c] Source: (NEA, 2002, p. 214).

[d] Source: MIT (2003).

[e] Source: (NEA, 1994, p. 115). This data was taken from reprocessing experience with spent LWR fuel at Sellafield, GB. During this study, the same flow parameters have been adopted for the reprocessing of FBR fuel.

[f] Data regarding composition of fresh and spend FBR fuel was taken from (NEA, 2002, p. 209).

Table 2.5: Investment costs (γ_I), fixed and variable operation and maintenance costs (γ_{fix}, γ_{var}) for nuclear technologies.

technology	γ_I		γ_{fix}		γ_{var}	
tnr[a]	2500	\$/kW	0.025	a^{-1}	4.12	\$/kWa
fnr[b]	4500	\$/kW	0.033	a^{-1}	5.35	\$/kWa
tnrfp[a]	10	\$/tHM a^{-1}	0	a^{-1}	980	\$/kgHM
tnrrep[a]	10	\$/m^3a^{-1}	0	a^{-1}	1082	\$/L
tnrdd[c]	10	\$/m^3a^{-1}	0	a^{-1}	200	\$/L
fnrfp[d]	10	\$/tHM a^{-1}	0	a^{-1}	980	\$/kgHM
fnrrep[c]	10	\$/m^3a^{-1}	0	a^{-1}	18000	\$/L
fnrdd[c]	10	\$/m^3a^{-1}	0	a^{-1}	200	\$/L
hlwis2ts[e]	5133	\$/m^3a^{-1}	0	a^{-1}	373	\$/L
ilwis2ts[e]	596	\$/m^3a^{-1}	0	a^{-1}	69	\$/L
llwis2ts[e]	10	\$/m^3a^{-1}	0	a^{-1}	3	\$/L
pu2hlw[f]	5133	\$/m^3a^{-1}	0	a^{-1}	373	\$/L

[a] Source: MIT (2003).

[b] Investment costs are based on own assumptions. Operation and maintenance costs 30 % higher than those of thermal reactors were assumed.

[c] Source: (NEA, 2002, p. 214).

[d] The same economic parameters as for LWR fuel production were used.

[e] Source: (NEA, 1994, p. 115). No value was given for the capital cost of LLW treatment.

[f] For the conditioning of plutonium the same parameters as for HLW conditioning were used (from (NEA, 1994, p. 115)).

Table 2.6: Investment costs (γ_I), fixed and variable operation and maintenance costs (γ_{fix}, γ_{var}) for non-nuclear technologies. If not noted otherwise, investment costs are taken from IEA/OECD (2003), and variable o&m costs are taken from IEA (2005b).

technology	γ_I		γ_{fix}		γ_{var}	
ngcc	500	$/kW	0.02	a^{-1}	30.0	$/kWa
ngccc [a]	1100	$/kW	0.02	a^{-1}	45.0	$/kWa
ngt	400	$/kW	0.02	a^{-1}	20.0	$/kWa
pc	1150	$/kW	0.02	a^{-1}	45.0	$/kWa
pcc [a]	1900	$/kW	0.02	a^{-1}	67.5	$/kWa
hydro	2250	$/kW	0.02	a^{-1}	60.0	$/kWa
wind	1100	$/kW	0.02	a^{-1}	30.0	$/kWa
spv	4500	$/kW	0.02	a^{-1}	50.0	$/kWa
tdel [b]	1575	$/kW	0.01	a^{-1}	0	$/kWa
ccscomp [c]	10	$/tC a^{-1}	0.05	a^{-1}	0	$/tC
ccspipe [c]	10	$/tC a^{-1}	0.01	a^{-1}	0	$/tC
ccsinje [c]	10	$/tC a^{-1}	0.03	a^{-1}	0	$/tC
ccsmoni [c]	10	$/tC a^{-1}	0.01	a^{-1}	0	$/tC

[a] Source for investment costs of powerplants with carbon sequestration: IPCC (2005). Variable o&m costs are assumed to be 50 % higher than without sequestration.

[b] Source for investment costs of tdel: Bauer (2006)

[c] Source for CCS chain data: Bauer (2006)

Table 2.7: Technological parameters for non-nuclear technologies. The output of renewable energy technologies is affected by site quality as well (resource availability factor ν_r, see table 2.3).

Technology	Transformation factor (η)		Load factor (ν)		Lifetime (t_l)	
ngcc	0.55	(-)	0.85	(-)	35	a
ngccc	0.47	(-)	0.85	(-)	35	a
ngt	0.38	(-)	0.85	(-)	35	a
pc	0.42	(-)	0.85	(-)	40	a
pcc	0.35	(-)	0.85	(-)	40	a
hydro	0.80	(-)	0.85	(-)	70	a
wind	0.45	(-)	0.85	(-)	30	a
spv	0.15	(-)	0.85	(-)	30	a
tdel	0.95	(-)	0.90	(-)	60	a
tnr	45.21	TWa/MtHM	0.75	(-)	40	a
fnr	131.51	TWa/MtHM	0.75	(-)	40	a
ccscomp	1.00	(-)	0.90	(-)	50	a
ccspipe	0.99	(-)	0.90	(-)	50	a
ccsinje	1.00	(-)	0.90	(-)	50	a
ccsmoni	1.00	(-)	0.90	(-)	50	a

Technical parameters

Table 2.7 shows efficiency factor, availability factor and maximum technological lifetime for non-nuclear technologies. Most effort has been put into the efficiency data. The load factor values are still generic: Values have been set to 0.75 for nuclear reactor technologies, and 0.85 for all other electricity generation technologies.

For transportation of captured CO_2 via pipelines a loss of 1 % is assumed. For all other CCS technologies the efficiency factor is 1.

Figure 2.5.6 shows the vintage depreciation curves for all technologies. These parameters are, at the present state, not based on references and need to be revised for further studies.

Emissions

Table 2.8 shows the emission coefficients of technologies that emit CO_2 [31]. Power plants with carbon capture also emit *captured* CO_2. It is assumed that 90 % of the CO_2 that is generated by the combustion process is captured. Furthermore it is assumed that 1 % of the captured CO_2 is lost during transport via pipelines.

[31] For the transformation of the specific CO_2 emissions the factors 15.2 GtC/ZJ and 26.0 GtC/ZJ of primary energy natural gas and coal, respectively, have been used IPCC (2001a).

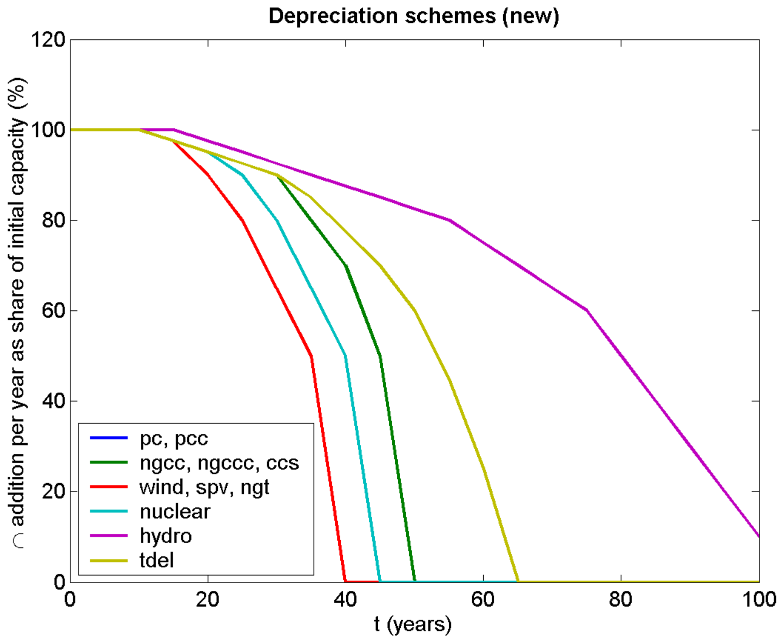


Figure 2.22: Depreciation curves for all technologies. The figure shows the share of initially installed capacitiy that is in operation after a given time range.

Table 2.8: Emission coefficients

technology	emission type y	emission factor λ	
ngt	co2	0.479	GtC/TWa
ngcc	co2	0.479	GtC/TWa
ngccc	co2	0.048	GtC/TWa
pc	co2	0.820	GtC/TWa
pcc	co2	0.082	GtC/TWa
ngccc	cco2	0.431	GtC/TWa
pcc	cco2	0.738	GtC/TWa
ccspipe	co2	0.010	GtC/GtC

Table 2.9: Learning parameters

technology	learn. rate r_L(%)	floor cost γ_F ($/kW)	initial cum. cap. κ_0 (TW)
spv	20	1000	0.0044 [a]
wind	7	700	0.0660 [b]
ngccc	5	1000	0.0100
pcc	5	1400	0.0100

[a] Based on Quaschning (2006)

2.5.7 Learning effects

In this study only four technologies were considered as 'learning' technologies:

- Wind turbines
- Photovoltaic
- Gas and coal power plants with CO_2 capture.

For all other technologies fixed cost parameters were assumed. For conventional technologies (fossil fuel based powerplants without carbon capture) it was assumed that the future learning potential can be neglected. Nuclear power plants were modeled as non-learning technologies as well. Although considerable resources are invested in the improvement of nuclear technology, it is doubtful whether its economical development can be modeled via a learing curve. On the one hand, there is always only a small number of nuclear power plants that is produced, because the size of each unit is very big. This, combined with regional variation due to differing national regulations decreases standardization and automatization effects. On the other hand, the economics of nuclear power generation is affected by other factors like increasing security demands which as a counterbalance to learning effects. Some references state a net cost increase of nuclear power generation over time (e.g. van Leeuwen und Smith (2005)).

However, to reflect the considerable uncertainty about the economic parameters of nuclear energy, the cost parameters of both thermal and fast reactor technologies have been varied during the multi-run experiments which will be presented in section 3.2.

Table 2.9 shows the model parameters associated with learning effects. Due to the learning curve approch that was applied the initial cumulated capacity must not be zero because that would result in an inifinite initital gradient of the learning curve. Therefore, for the CCS powerplant technologies a installed capacity of greater than zero was applied. This is not too far-fetched as there already exists great experience with fossil fuel power generation without carbon capture, and this is most likely to cause spill-over effects to the advantage of the new technologies.

The floor costs of photovoltaic were based on van der Zwaan und Rabl (2003). For the other technologies, a ratio of floor costs to initial investment costs of about 70 % was assumed.

Table 2.10: Initial mix of electricity generation. See text for explanation.

resource	Share (%) IEA (2005a)	model data	model technology [a]
oil	6.9	0.00	-
natural gas	19.4	20.76	ngt + ngcc
coal	40.1	42.90	pc
hydropower	15.9	17.01	hydro
nuclear	15.8	16.90	tnr
wind energy	1.5	2.35	wind
solar	0.1	0.07	spv
Total	99.7	100.00	

[a] See table A.5 for a list of abbreviations.

2.5.8 Initial calibration

Initial mix of technologies The data for the relative share of initial electricity generation (timestep t_0, year 2005) for each technology was based on IEA (2005a). The given data was adapted to suit the needs of the model. Table 2.10 shows the values as they are given in the reference, and the values that were used in the model. The following changes have been made:

1. *Substitution of oil:* As the consumption of oil for electricity generation is not considered in this study, the relative shares of all other technologies has been increased proportionally to substitute oil as an energy source. The share of oil has been distributed among the other technologies weighted by their respective own share.
2. *Assigning technologies to resources:* The share of gas-based electricity production was distributed equally to gas turbines and combined-cycle powerplants. The remaining resource types were assigned to the respective model technology that uses this technology (see table).
3. *Share of wind energy and photovoltaic:* Because of data mismanagement these parameters do not coincide with those in the reference. The correct values would have been 1.61 % for wind and 0.11 % for photovoltaic.

This data is used to calculate the absolute initial capacity for each technology that is needed to satisfy all internal and external electricity demands. Please refer to section 2.1.2 for details on how the initial calibration is implemented in genEris.

Spin-up of initial capacities

As all investments in genEris have a limited lifetime, it also necessary to define the age of the capacities that have been installed *before* the initial starting point, and that are in operation at t_0. Figure 2.5.8 shows the spin-up development for all technologies that contribute to the generation of electricity at t_0. The vertical axis shows the annual

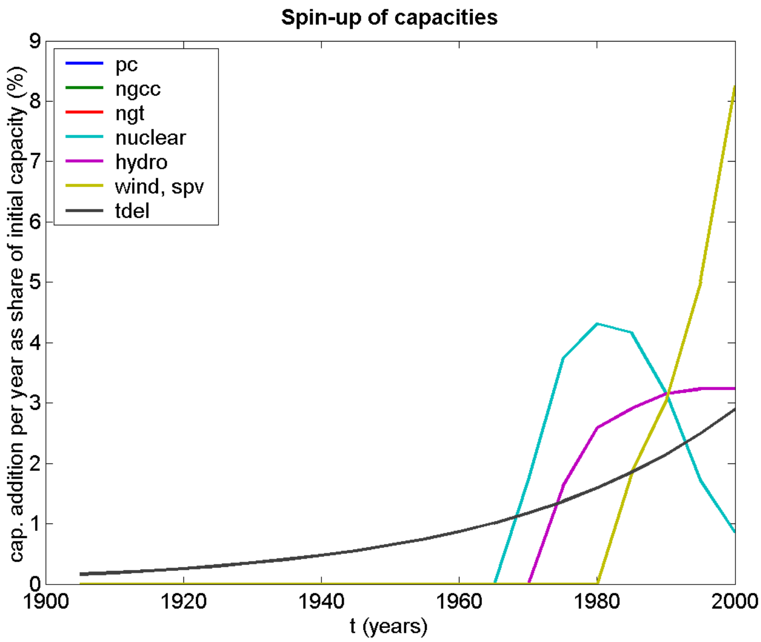


Figure 2.23: *Initial calibration:* Spin-up factors of technologies. These curves decribe when the capacities initially available in the model have been installed.

capacity additions as a percentage of the capacity that is available at the first model timestep. The area under each curve equals 100 %.

3 Results and Discussion

In this chapter I will report on the experiments that have been conducted, and discuss the results. It is divided into two parts: Section 3.1 presents four representative single model runs and introduces the various types of results. Section 3.2 covers several multi-run experiments that have been conducted to explore the effects of the variation of various model parameters.

In the text the names of technologies, energy types, variables and parameters are written out whereever it is possible. In the axis labels and legends of the graphics as well as in tables abbreviations and symbols have been used. A list of symbols, abbreviations and units can be found in the appendix[1].

3.1 Single-run experiments

There is considerable uncertainty about several parameters that are used in the energy system model – and some of these uncertain parameters have a strong impact on the model results. To reflect this uncertainty, no *central case* will be presented in this study. Instead, a group of four different scenarios will be discussed. These scenarios differ in the values of three key parameters that influence the competitiveness of the three main mitigation options – nuclear power, renewable energy and CCS. The following parameters have been used to distinguish the four base cases:

1. *Investment costs of fast reactors* γ_I*(FNR)*: As of today, there is only little experience with fast reactors on a commercial scale. The investment costs for this technology are uncertain. For nuclear reactors, investment costs contribute a large share of the total electricty generation costs, so this factor is likely to influence the fate of the nuclear option significantly.
2. *Floor costs of photovoltaic* γ_F*(SPV)*: The investment costs of photovoltaic are very high today, but significant cost reductions are expected to occur due to learning effects. The variation of the floor costs represent the uncertainty about how far the costs can decrease.
3. *Fossil fuel costs*: The development of fossil fuel extraction costs will determine if the CCS option will become economically feasible. The Rogner curve parameters for coal and gas have been varied to represent the uncertainty about this issue.

Table 3.1 lists the four base cases along with the respective values for the three key parameters. All technology options are available in all cases (no technology has been 'turned off' exogeneously).

[1]Unfortunately, due to a mistake that I did not manage to correct due to time limitations, depreciated abbreviations for nuclear reactor technologies are used in some graphics. So, the reader is kindly asked to translate the occasional LWR (light water reactor) and FBR (fast breeder reactor) into TNR (thermal nuclear reactor) and FNR (fast nuclear reactor). Sorry for the inconvenience.

Table 3.1: Parameter assumptions for the four *base scenarios*. γ_F(SPV): floor costs of photovoltaic. γ_I(FNR): Investment costs of fast nuclear reactors. RE: Renewable Energy. All parameters that are not mentioned here are set to the standard values that are documented in section 2.5.

	γ_F(SPV) ($/kW)	γ_I(FNR) ($/kW)	Fossil fuel costs [a]
Pro RE	1000	4500	high
Pro Nuclear	1500	3500	high
Fossil & RE	1500	4500	low
Fossil & Nuclear	1500	3500	low

[a] See table 2.2 for details on the Rogner parameters.

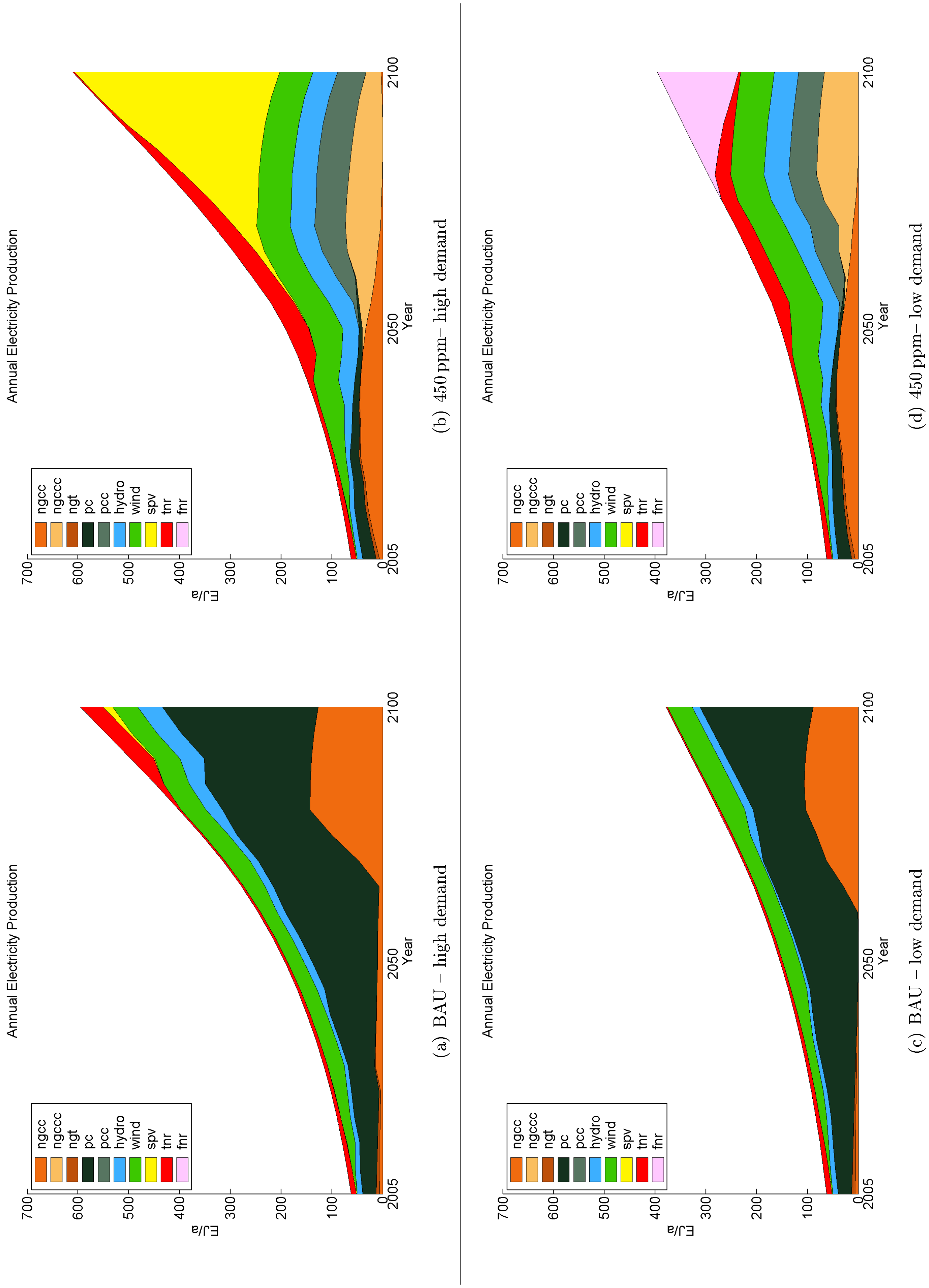
Production of electricity The mix of electricity generation for all four scenarios is shown in figures 3.1, 3.2, 3.3 and 3.4. For each base case, four pictures show the electricity generation timepath for BAU and 450 ppm stabilization scenario (left side – right side), and for high and low demand scenario (upper half – lower half)[2]. Several interesting observations can be made:

- In all scenarios, a variety of different technologies is used. Renewable energy occurs in the *Pro Nuclear* case, and thermal nuclear reactors are used in the *Pro RE* case.
- In the BAU emission scenarios, photovoltaic is not used at all, not even in the *Pro RE* case. This is a very surprising result which will be examined later on during the multi-run experiments.

The technologies can be grouped according to their behaviour across the different cases:

- *Technologies that are always used:* Wind energy, hydropower and thermal reactors are used in all scenarios. In the 450 ppm scenarios, the total capacity of wind energy and hydropower is higher in the BAU scenarios, but they remain fairly constant in the four base cases. For thermal reactors, the total capacity remains fairly constant, but the point in time when they are employed varies significantly. This behaviour will be discussed further in the next paragraphs.
- *Technologies that are not used at all:* Natural gas turbines are phased out very quickly in all scenarios. This reflects the effects of rising gas prices, and the availability of a technology that uses the same resource with a higher efficiency (gas combined cycle plants).
- *Technologies that are only used in some scenarios:* This category contains photovoltaic, fast reactors, and CCS technologies (gas and coal). CCS is only used in the two cases with cheap fossil fuel (*Fossil & Nuclear* and *Fossil & RE*) – for obvious reasons.

[2]See section 2.5 for a description of the emission and demand scenarios.



(a) BAU – high demand

(b) 450 ppm– high demand

(c) BAU – low demand

(d) 450 ppm– low demand

Figure 3.1: *Fossil & RE case:* Electricity production.

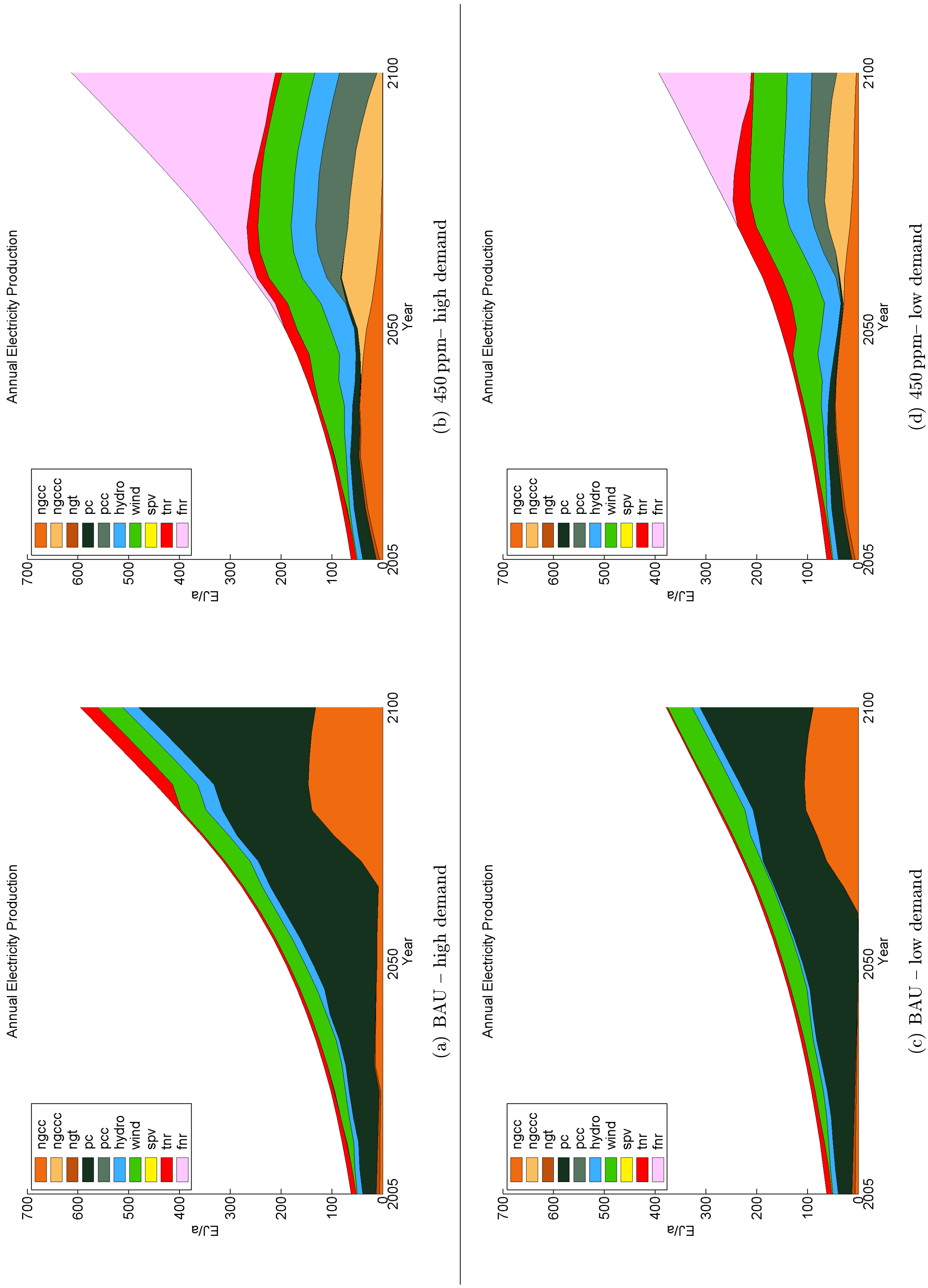
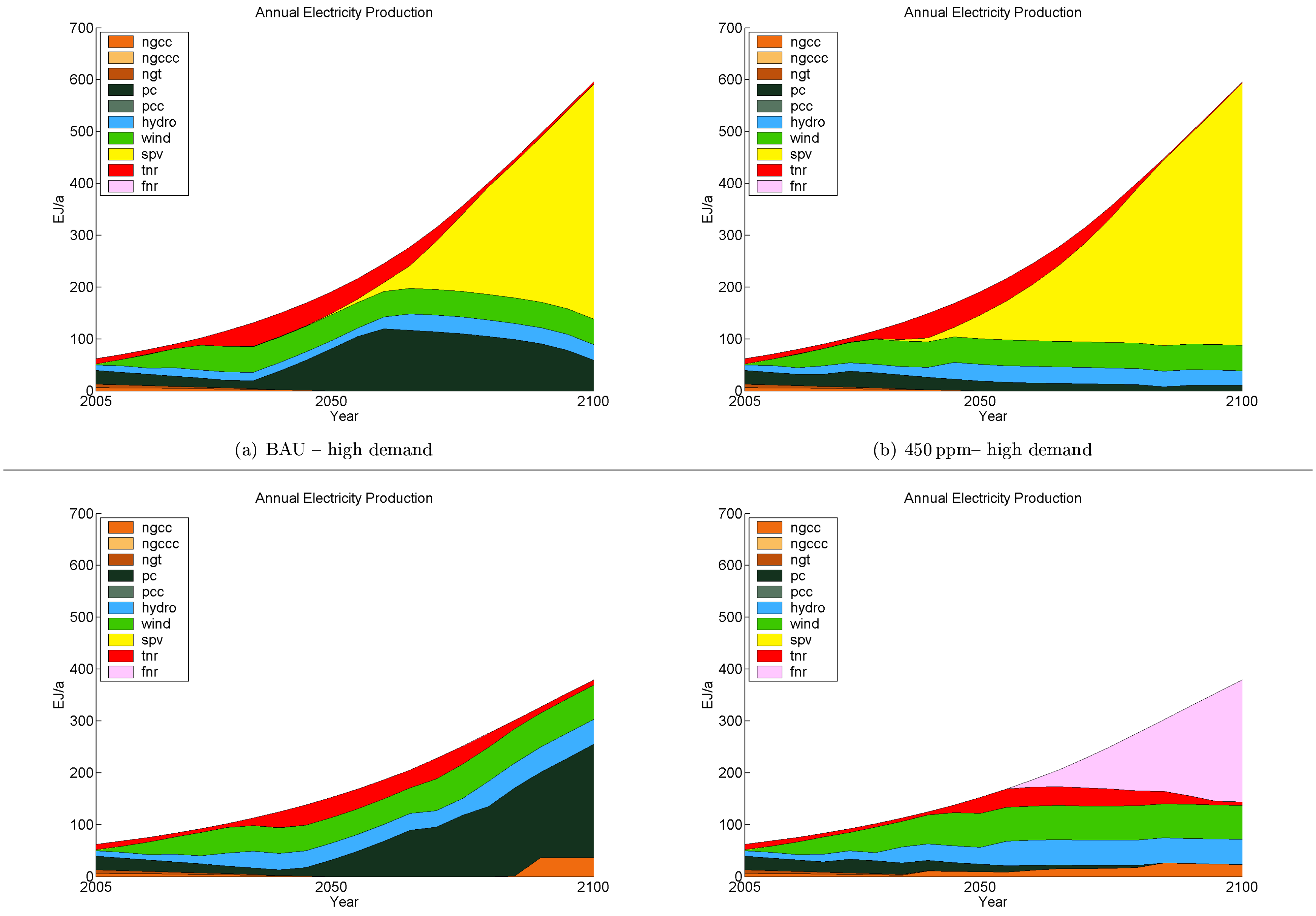


Figure 3.2: *Fossil & Nuclear base case:* Electricity production.



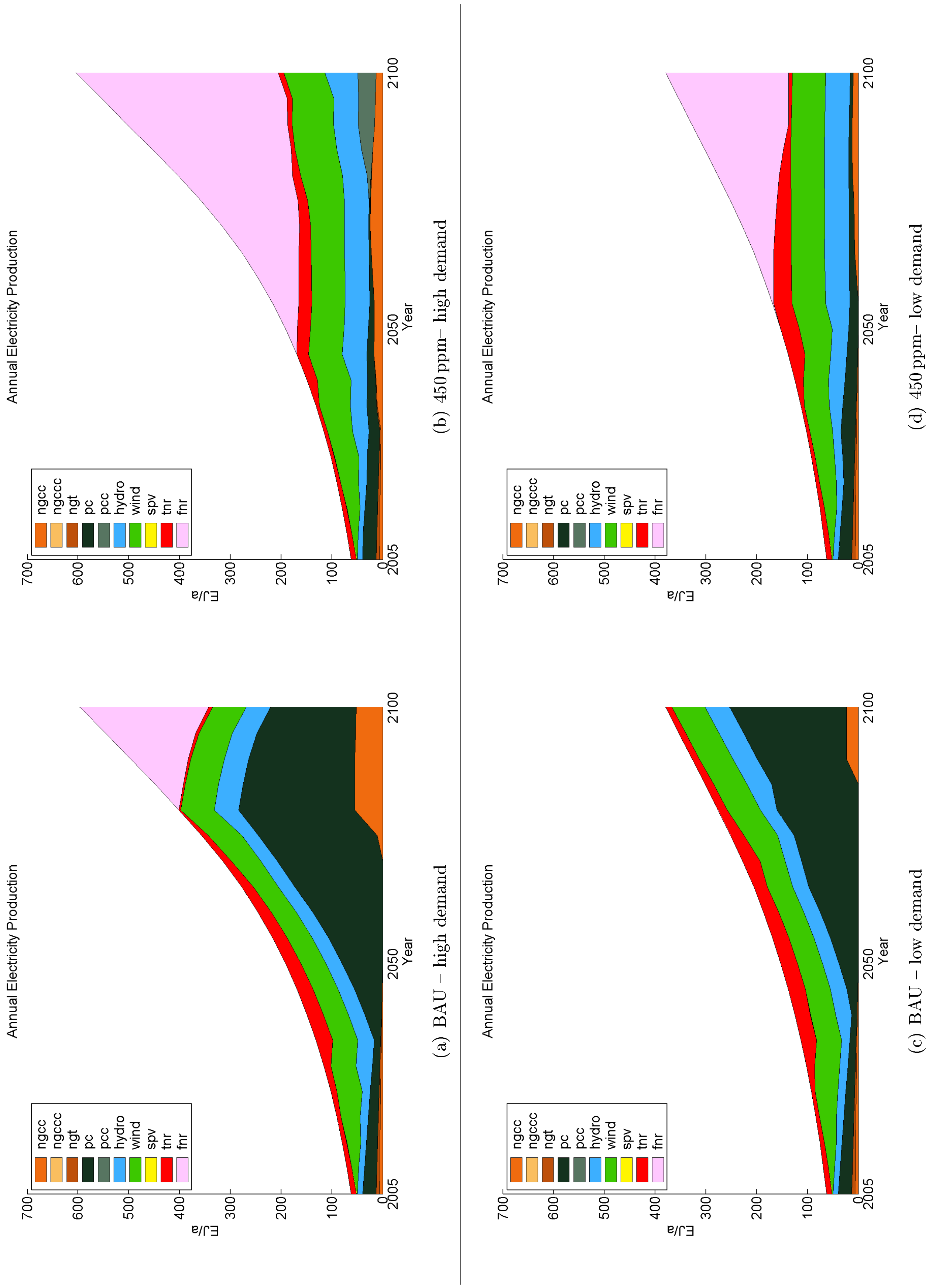
(a) BAU – high demand

(b) 450 ppm– high demand

(c) BAU – low demand

(d) 450 ppm– low demand

Figure 3.3: *Pro RE case:* Electricity production.



(a) BAU – high demand

(b) 450 ppm– high demand

(c) BAU – low demand

(d) 450 ppm– low demand

Figure 3.4: *Pro Nuclear case:* Electricity production.

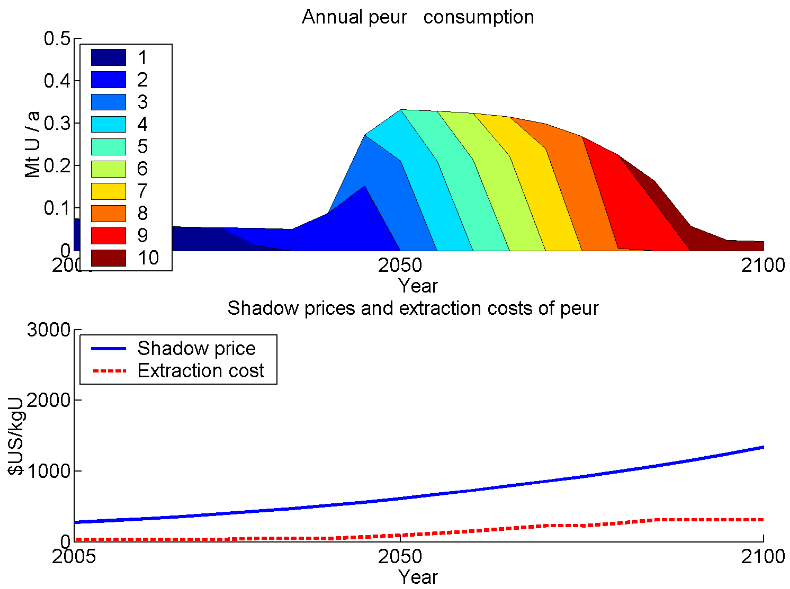


Figure 3.5: Annual consumption and shadow price of uranium. (Base case: *Fossil & RE*, emission scenario: 450 ppm)

- *Technologies that are always used, but with different shares:* Gas combined cycle and coal power plants are used in all scenarios, but their share varies according to the fossil fuel costs.

In the following, several aspects of these graphics will be discussed in detail, highlighted by single graphics of further model results. Most of these results will be taken from the *Fossil & RE* case because it utilizes a broad variety of technology options.

Thermal nuclear reactors Thermal reactors are used in all cases and scenarios. In the 450 ppm policy scenario the cumulated electricity production by thermal reactors is fairly constant, only the timepath of it's use varies between the different base cases. Figure 3.5 shows the annual uranium extraction in the *Fossil & RE* case (450 ppm scenario). The different cost grades are distinguished by colors. All ten available cost grades are used. Obviously, the use of thermal reactors is not limited by the availability of more economic alternatives but by the limited uranium resources. The extraction costs and the shadow price of uranium are shown in the lower graph. Due to the scarcity of the resource the shadow price rises to a high 1200 $/kgU in 2100.

Fast nuclear reactors and photovoltaic The case of photovoltaics and fast breeders is very interesting: In the BAU scenarios, they are only used at all in the case of high demand assumptions. In cases where they are used, they are always introduced after 2050. In these cases, they always play a very dominant role in the second half of the century. They are never used *together*. These two technologies have some common characteristics: Both have high initial investment costs, and they are the only technologies that are not constrained by limited potentials or fuel resources, which makes them the only real *backstop technologies* in this model[3]. If, for all four base cases, the BAU / high demand scenarios are compared with the 450 ppm/ high demand scenarios, it can be seen how emission restrictions accelerate the transition to either photovoltaic or fast reactors.

It is interesting to note that in the 450 ppm/ low demand scenarios, in all four base cases fast reactors are used instead of photovoltaic. This also holds for the *Pro RE* and *Fossil & RE* base cases. In these scenarios two local optima exists where either the one or the other backstop technology is favoured. The solver algorithm chooses the 'nuclear' optimum in all cases, ignorant to the fact that under certain parameter assumptions choosing photovoltaic would result in lower total costs. More details on the issue of multiple local optima can be found in section 3.2.4.

Fossil fuels Not surprisingly, the use of fossil fuel (gas and coal) without CCS is mainly restriced to the BAU scenarios. In the 450 ppm scenarios these options are substituted by other technologies. In the case of low fossil fuel costs, there is a continuous use of gas and coal, after 2050 via technologies that use CCS. In the case of high fossil fuel costs, gas and coal play a very minor role, not even in the first decades. Figure 3.6 compares the annual consumption of coal and gas in the *Fossil & RE* case for both BAU and 450 ppm stabilization scenario. Even in the BAU scenario, not all ten grades are used for either coal or gas resources. The shadow prices are lower in the policy scenario, as the use of fossil fuels is limited by emission costraints.

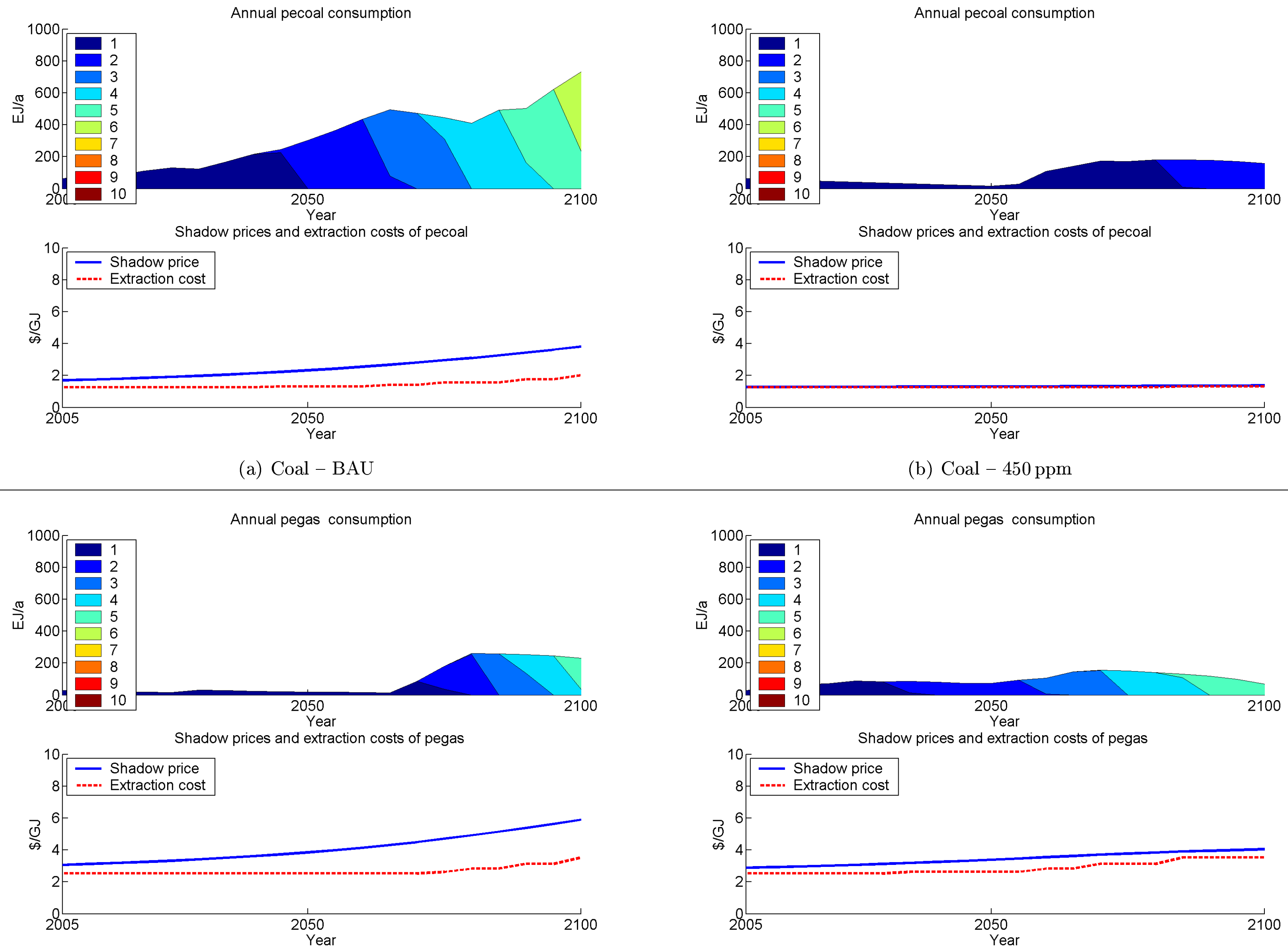
The figure shows that in the parametrization that was used for this study, the fossil fuel resources are quite large. Even without a cap on emissions the gas resources are not depleted until the yeaer 2100. It would be interesting to decrease the resource base – this could be done in further studies.

Carbon Capture (CCS) The role of CCS cleary depends on the fossil fuel prices – this option is only used in the two cases where the low fuel price scenario was used. Both available energy sources (gas and coal) are used simultaneously and to a similar amount, regardless of the demand scenario. Interestingly, CCS is always used in the second half of the century. In these scenarios this option is not used to faciliate the transition to an energy system that is based on renewable or nuclear energy, but to satisfy the increasing demand at the end of the time horizon. In the transition phase, wind and hydropower, and in some cases, thermal nuclear reactors are used. Figure 3.7 shows the annual emissions and the annual sequestration of CO_2 in the *Fossil & RE* case (450 ppm scenario). It becomes evident that the binding constraint for the use of CCS is not the size of the available deposits, but the constraint on emissions.

Potentials of renewable energy Figure 3.8 shows to which extent the available potentials of renewable energy sources are utilized (*Fossil & RE* case, 450 ppm scenario). It also shows the marginal costs of the constraint for each grade. The marginal costs become greater than zero if the constraint is binding, and their value decreases with the quality of the respective grade. For no energy source all available grades[4] are used. For photovoltaic the contraint for the first grade is not binding which means that the first

[3] In fact, restrictions do exist for both technologies. But the maximum potential of photovoltaic is very high, and uranium consumption of fast reactors is very low, so that these constraints are not binding.

[4] There are 7 grades for wind and photovoltaic and 4 grades for hydropower.



(a) Coal – BAU

(b) Coal – 450 ppm

(c) Gas – BAU

(d) Gas – 450 ppm

Figure 3.6: Annual consumption and shadow price of coal and gas (Base case: *Fossil & RE*, emission scenario: BAU)

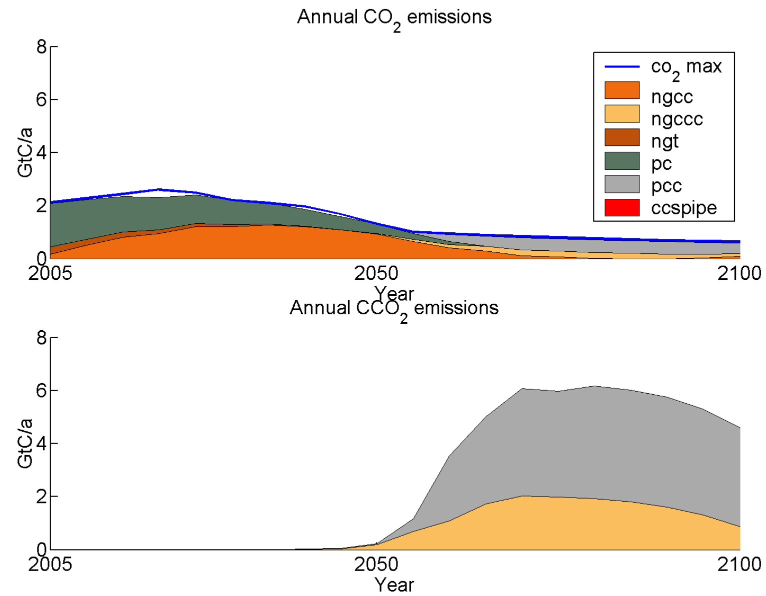


Figure 3.7: Annual CO_2 emissions and CO_2 sequestration. (Base case: *Fossil & RE*, emission scenario: 450 ppm)

grade is big enough to satisfy all demands for that energy source. This is owed to the size of the overall technological potential of photovoltaic. As the total potential is divided into a limited number of equally sized grades, these grades themselves are particularily big for this technology[5].

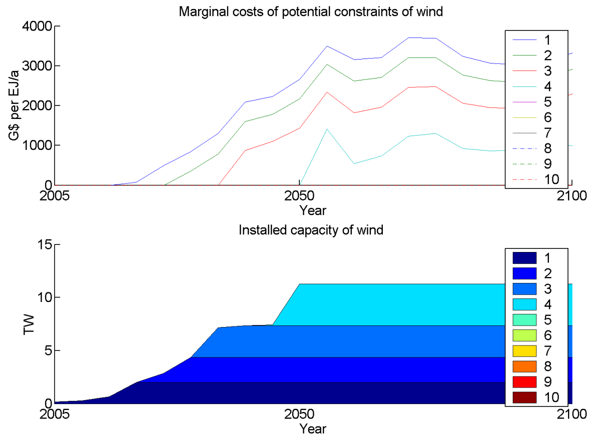
Investment costs of learning technologies Figure 3.9 shows the development of the investment costs of learning technologies (Base case: *Fossil & RE*, emission scenario: 450 ppm). It shows how especially photovoltaics benefit from substantial learning effects. The costs reductions are achieved quite quickly because the learning rate is high, and the initial cumulated capacity is low. See section 3.2 for a more detailed assessment of the significance of the learning parameters of this technology.

Electricity production costs Figures 3.10 and 3.11 shows the specific costs of electricity production for the different technologies. Two different methods have been used to calculate these figures: On the right-hand side, for each model run the total costs associated with a technology have been divided by the total amount of electricity produced by it. On the left-hand side, for comparison, the electricity production costs have been calculated via the annuity method by using the initial model parameters[6]. Those will henceforth be referred to as annuitiy-based costs. Several things catch the eye:

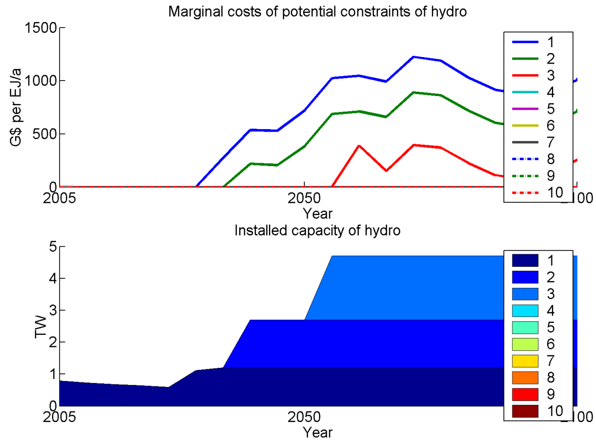
- As the initial investment, operation and maintentance costs are the same for all base cases, the annuity-based costs only differ with regard to the fossil fuel costs.

[5]This issue should be taken care of in future work. It will certainly pose less of a problem when the energy system is divided into regions because of the uneven geographic distribution of solar potential.

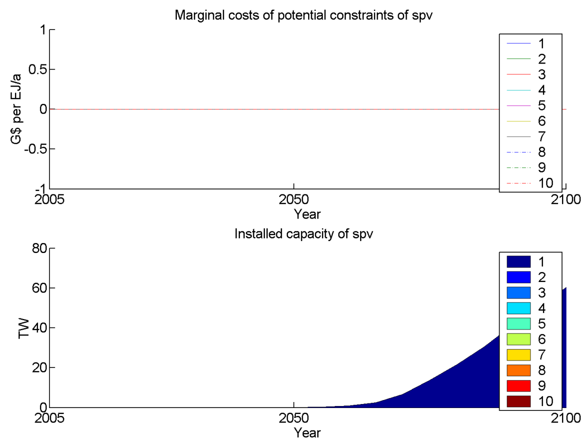
[6]As they are used in the first timestep of the model: no learning effects, first grade for exhaustible resources and potentials of renewable energy.



(a) Wind energy



(b) Hydropower



(c) Photovoltaic

Figure 3.8: Utilization of the potential of renewable energy sources (Base case: *Fossil & RE*, emission scenario: 450 ppm).

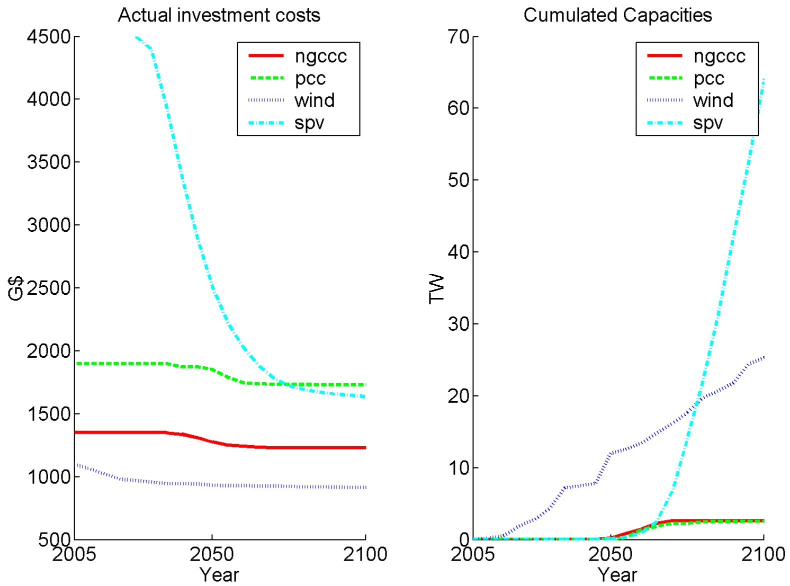
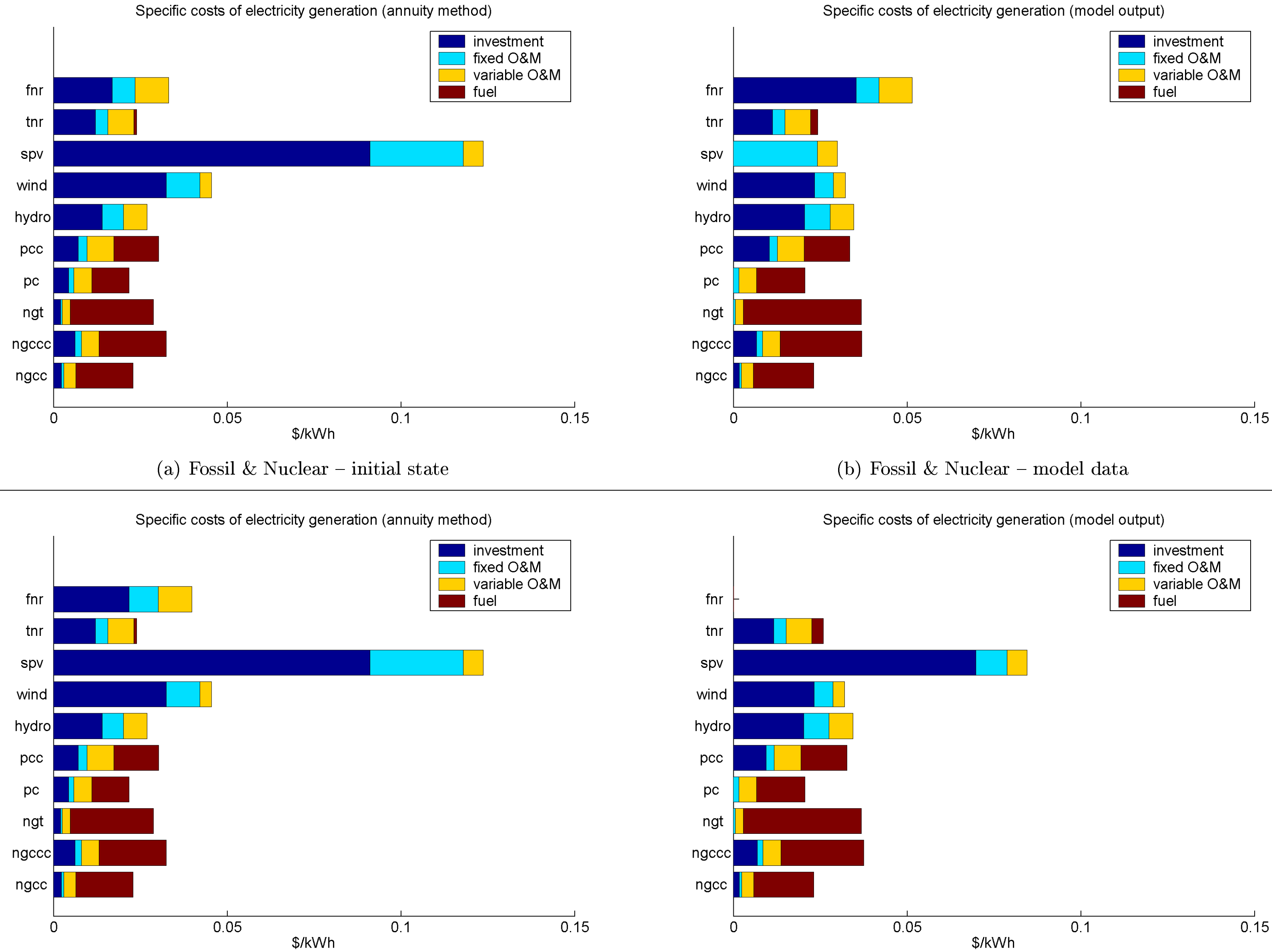


Figure 3.9: Time paths of investment costs for learning technologies (Base case: *Fossil & RE*, emission scenario: 450 ppm.)

- The model-based costs vary significantly between the different base cases as the utilization of technologies varies, cumulated as well as intertemporally. The costs of technologies that are not used are zero; if there is no investment in a technology, only the O&M and fuel costs are shown. In the *Pro Nuclear* case, the costs for photovoltaic are high because photovoltaic is introduced during the last ten years of the time horizon. This can be regarded as an artifact. In the other cases the cost reduction for learning technogies (noteably wind energy and photovoltaic) can be seen clearly.

- The annuity-based costs are quite low when compared to those that can be found in literature. One reason for this is the fact that the discounting rate of the model (2 %) has been used as an interest rate. Usually, for short-term financial calculations higher interest rates are used. Figure 3.12 shows the annuity-based costs for the *Fossil & RE* scenario with an interest rate of 5 %.



(a) Fossil & Nuclear – initial state

(b) Fossil & Nuclear – model data

(c) Fossil & RE – initial state

(d) Fossil & RE – model data

Figure 3.10: *Base cases (low fossil fuel costs):*Electricity generation costs. High demand, 450 ppm. On the left side, the costs have been calculated using the initial parameters, ond the right hand side, the contribution of each technology to the total energy system costs have been extracted from the model results.

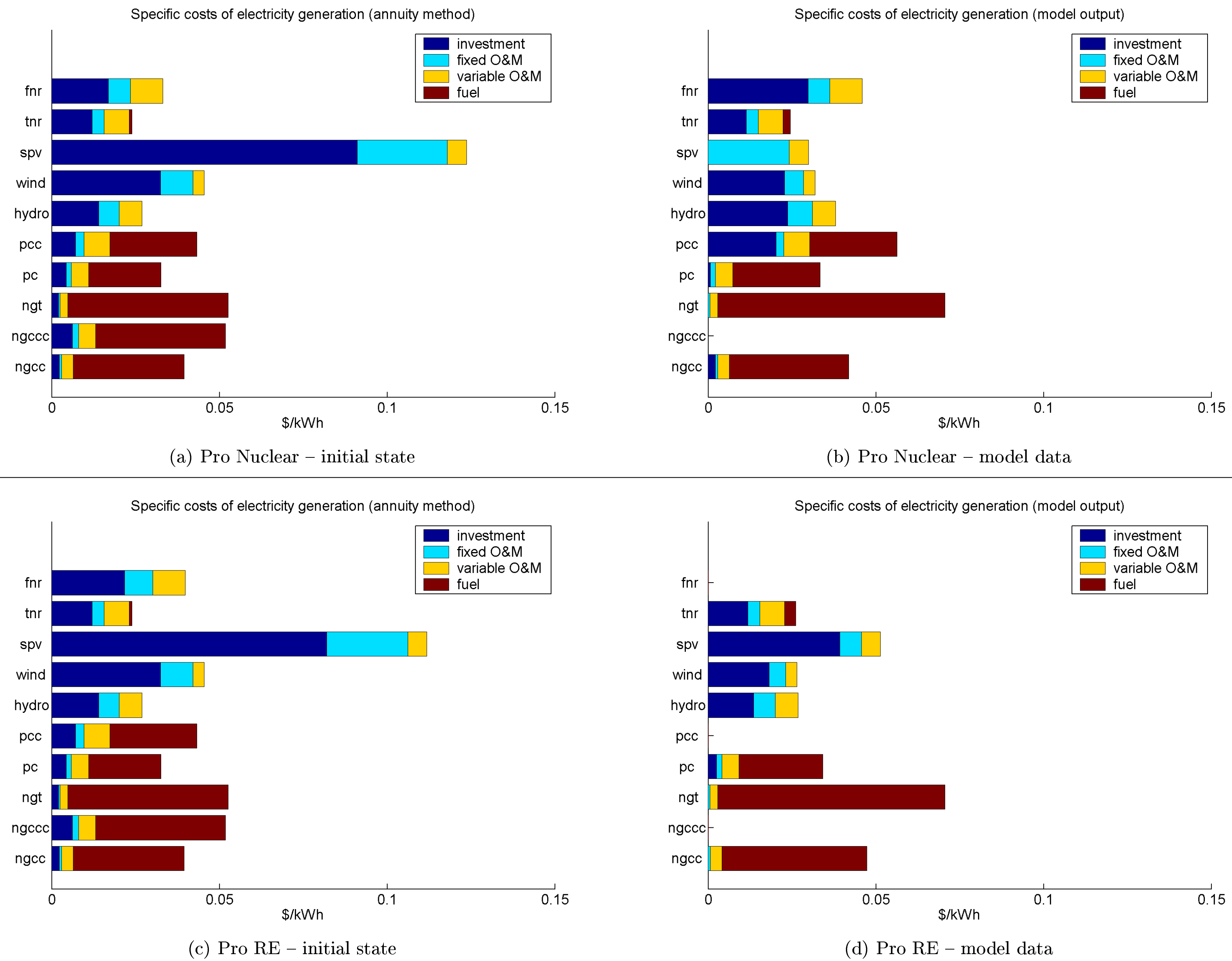


Figure 3.11: *Base cases (high fossil fuel costs):*Electricity generation costs. High demand, 450 ppm. On the left side, the costs have been calculated using the initial parameters, ond the right hand side, the contribution of each technology to the total energy system costs have been extracted from the model results.

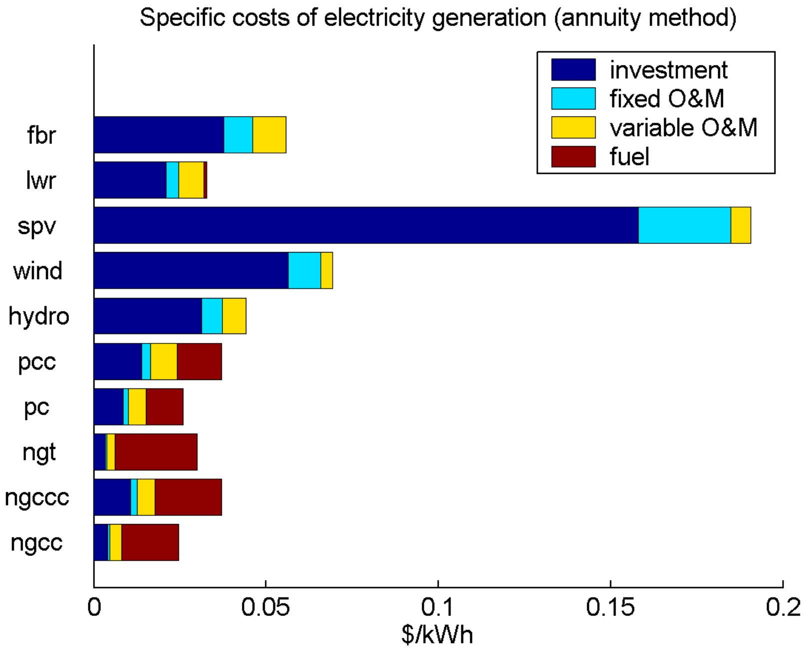


Figure 3.12: Annuity-based electricity production costs, interest rate 5 %. (Base case: *Fossil & RE*, emission scenario: 450 ppm.)

3.2 Multi-run experiments

In this section results from sensitivity analysis experiments will be presented. These experiments were designed to examine the role of some key model parameters.

- In the high demand scenarios, either fast nuclear reactors or photovoltaic seem to play a dominant role. A combination of both technologies is not observed in the four base cases. What are the conditions that make the model 'switch' between these two options?
- Under what circumstances is the CCS option used?
- Under emission constraints, thermal nuclear reactors are used in all four base cases. Under which conditions would this option become infeasible?
- Photovoltaics are not used at all in the low demand scenarios. Why is that so?

3.2.1 Design of the experiments

Choice of parameters During a *sensitivity analysis* a number of model parameters are varied in a defined range of values, and the model is solved once for every possible combination of them. All other parameters remain constant to ensure that the different solutions are comparable. During this study, for each experiment always four parameters were chosen for variation. Two of them are logical switches and are used in all experiments: one determines the demand scenario (high and low), the other one the emission scenario (BAU, 550 ppm, 500 ppm and 450 ppm). They will be referred to as *base parameters*. All possible combinations of them result in eight basic scenarios. The remaining two parameters are different for each experiment. They will be referred to as *experiment parameters*. Generally, the range of values for the experimental parameters is chosen quite generously and exceeds the range of uncertainty for the respective parameters to clearly show the behaviour of the model under different circumstances.

Table 3.2 gives an overview of the experiments that were conducted.

Graphical presentation Of the three dimensional graphics that will be presented in the following sections, each graphic represents the values of one decision variable for a fixed combination of values for the base parameters (demand and emission scenario) and all possible combinations of values for the experiment parameters. The experiment parameters are plotted on the x and y axes, the z axis represents the values of the decision variable. Blank values represent model runs that produced infeasible or nonoptimal results[7]. The values of the experiment parameters that coincide with the parameter choices in the four base cases (see previous section) have been marked with coloured triangles. It is important to note that, except for the first multi-run experiment[8], this equivalency only applies to the two experiment parameters that are displayed on the x

[7] Which does not mean that there is no optimal solution. In many cases, the erratic pattern of invalid model results and the relative smoothness of the result surface suggest that an optimal solution should exist and could be found by variation of starting values, additional constraints and solver options.

[8] *Floor costs of photovoltaics vs. costs of fast reactors.*

Table 3.2: Overview of the different multi-run experiments.

	Experiment parameters	Unit	Parameter range
1.	Floor costs of SPV	$/kW	500 – 2500
	Investment costs of TNR	$/kW	1500 – 4500
2.	Floor costs of SPV	$/kW	500 – 2500
	Investment costs of FNR	$/kW	2000 – 6000
3.	Floor costs of SPV	$/kW	500 – 2500
	Learning rate of SPV	%	0 – 32
4.	χ_1(gas) resp. χ_1(coal)	$/GJ	0 – 6 resp. 0 – 3
	χ_2(gas) resp. χ_2(coal)	$/GJ	0 – 56 resp. 0 – 28

Table 3.3: Floor costs of photovoltaics vs. costs of fast reactors: Choice of parameters.

	Experiment parameters	Unit	Parameter range
1.	Floor costs of SPV	$/kW	500 – 2500
	Investment costs of FNR	$/kW	2000 – 6000
	Fossil fuel costs	-	high
2.	Floor costs of SPV	$/kW	500 – 2500
	Investment costs of FNR	$/kW	2000 – 6000
	Fossil fuel costs	-	low

and y axis, as in most graphics the parameters that are not shown in the graphic are not identical for base cases and multi-run experiment.

3.2.2 Floor costs of photovoltaics vs. costs of fast reactors

In this experiment the floor costs of photovoltaic are varied together with the investment costs of fast reactors. The four base cases that were presented in section 3.1 indicate that there is a strong competition between these two technologies. Table 3.3 shows the parameter ranges that were chosen. The experiment was done twice, using the high and the fossil fuel cost scenario. This covers the parameter assumptions for all four base cases that were discussed in the previous section.

Figure 3.13 shows the cumulated share of electricity production for fast reactors and photovoltaic. In almost all model runs either photovoltaic or fast reactors play a quite dominant role, only in the BAU scenario parameter combinations exist where both of them are not used. There exists a very distinct 'switching line' where the model moves from one solution to the other one very apruptly. Both experiment parameters seem to be relevant for the choice between the two technologies.

Figure 3.14 shows the cumulated share of electricity production for the two CCS tech-

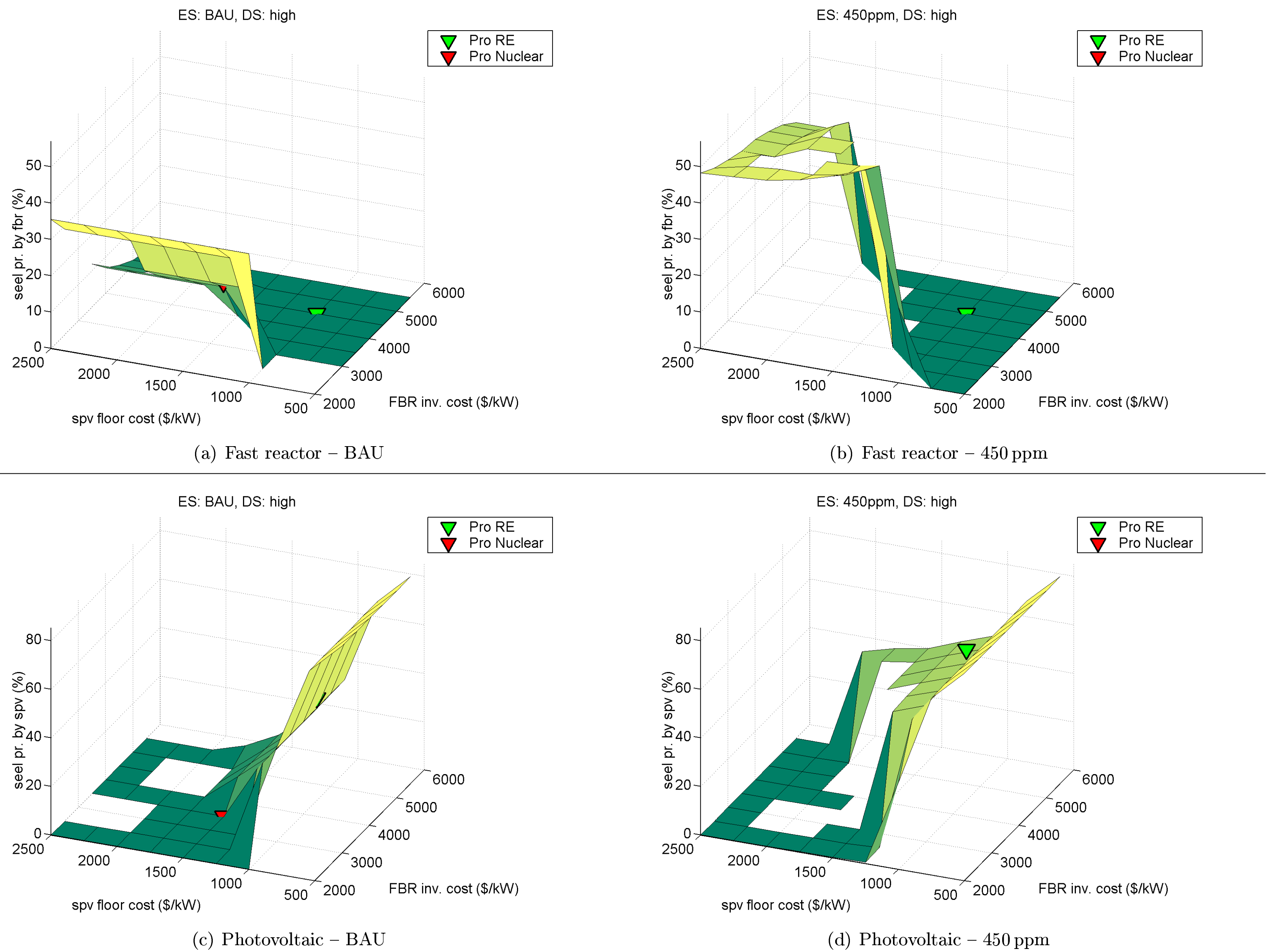


Figure 3.13: *Floor costs of photovoltaic vs. investment costs of fast reactors:* electricity production of fast reactors and photovoltaic (high demand).

Table 3.4: Floor costs of photovoltaic vs. investment costs of thermal reactors: Choice of parameters. maxwidth

Experiment parameter	Unit	Parameter range
Floor costs of SPV	$/kW	500 – 2500
Investment costs of TNR	$/kW	1500 – 4500

nologies (gas combined cycle and coal power plants). The color indicates the cumulated consumption of gas and coal, respectively. Figure 3.15 shows the cumulated amount of CO_2 that is captured and sequestrated. The figure shows that the decision whether to use CCS at all mainly depends on the cost assumptions for photovoltaic – if the photovoltaic floor costs are below a level of 1250 $/kW, the CCS option is not used at all. The extent to which the CCS option is used depends on the investment cost of fast reactors as well.

3.2.3 Floor costs of photovoltaics vs. investment costs of thermal reactors

This experiment was made to investigate the fact that thermal reactors are used in all of the base scenarios, and it tries to find out under which circumstances thermal reactors can be substituted by some other technology. Photovoltaics were chosen as a suitable candidate for this job – its technical potential is definitely big enough. All other parameters were the same as in the *Fossil & RE* base case.

Figure 3.16 show the relative share of the cumulated produced electricity, for both thermal reactors and photovoltaics. For thermal reactors, the color of the surface represents the cumulated uranium consumption. Several observations can be made:

- There obviously is a significant difference between the BAU and the other scenarios – an emission constraint gives an advantage to both technologies.
- The share of thermal reactors is not only affected by its own cost, but also by the floor costs of photovoltaics. This indicates that there is indeed a competitive relationship between these two technologies.
- The maximum share of thermal reactors is limited by the availability of uranium resources.
- The share of thermal reactors does not reach it's highest values when photovoltaic floor costs are at their highest values, but when they are in a range between 1000 and 1500 $/kW. Increasing photovoltaic floor costs over 1500 $/kW seems to give other technologies the opportunity to substitute not only photovoltaic, but also – to a certain extent – thermal reactors. Figure 3.17 show that this is correct for gas combined cycle powerplants and fast reactors.
- The share of photovoltaics, on the other hand, in invariant to the investment costs of thermal reactors, but only depends on it's own floor costs.

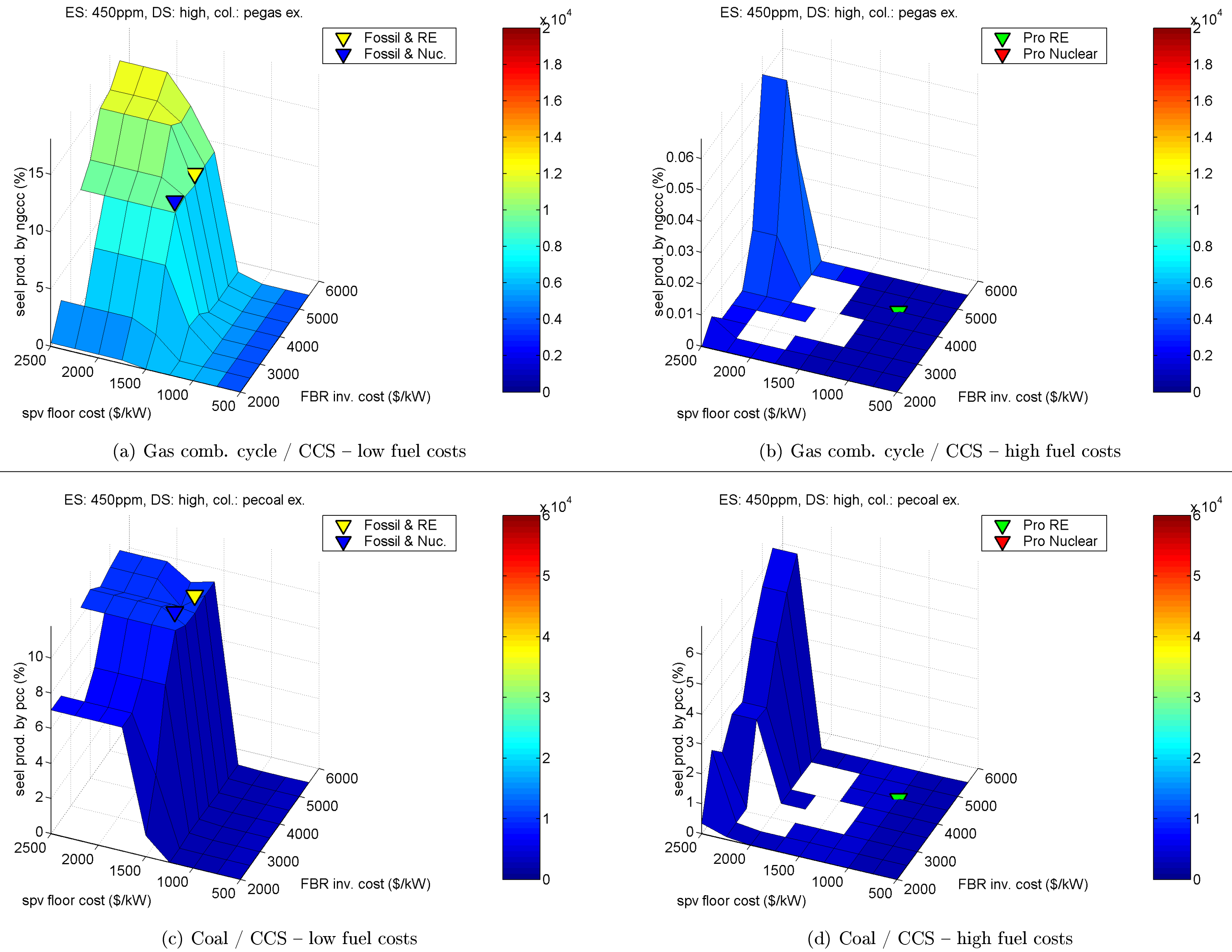
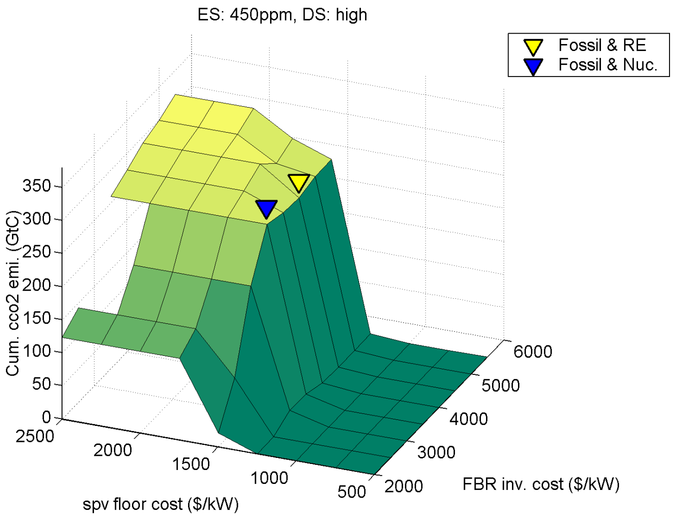
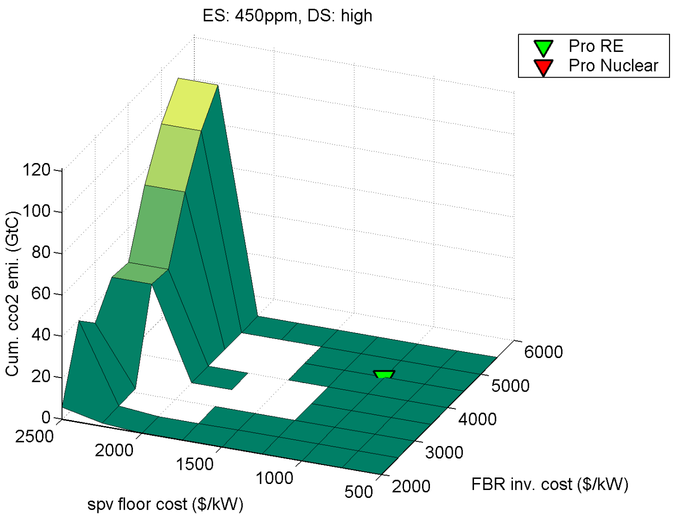


Figure 3.14: *Floor costs of photovoltaic vs. investment costs of fast reactors:* electricity production by CCS technologies (450 ppm scenario).

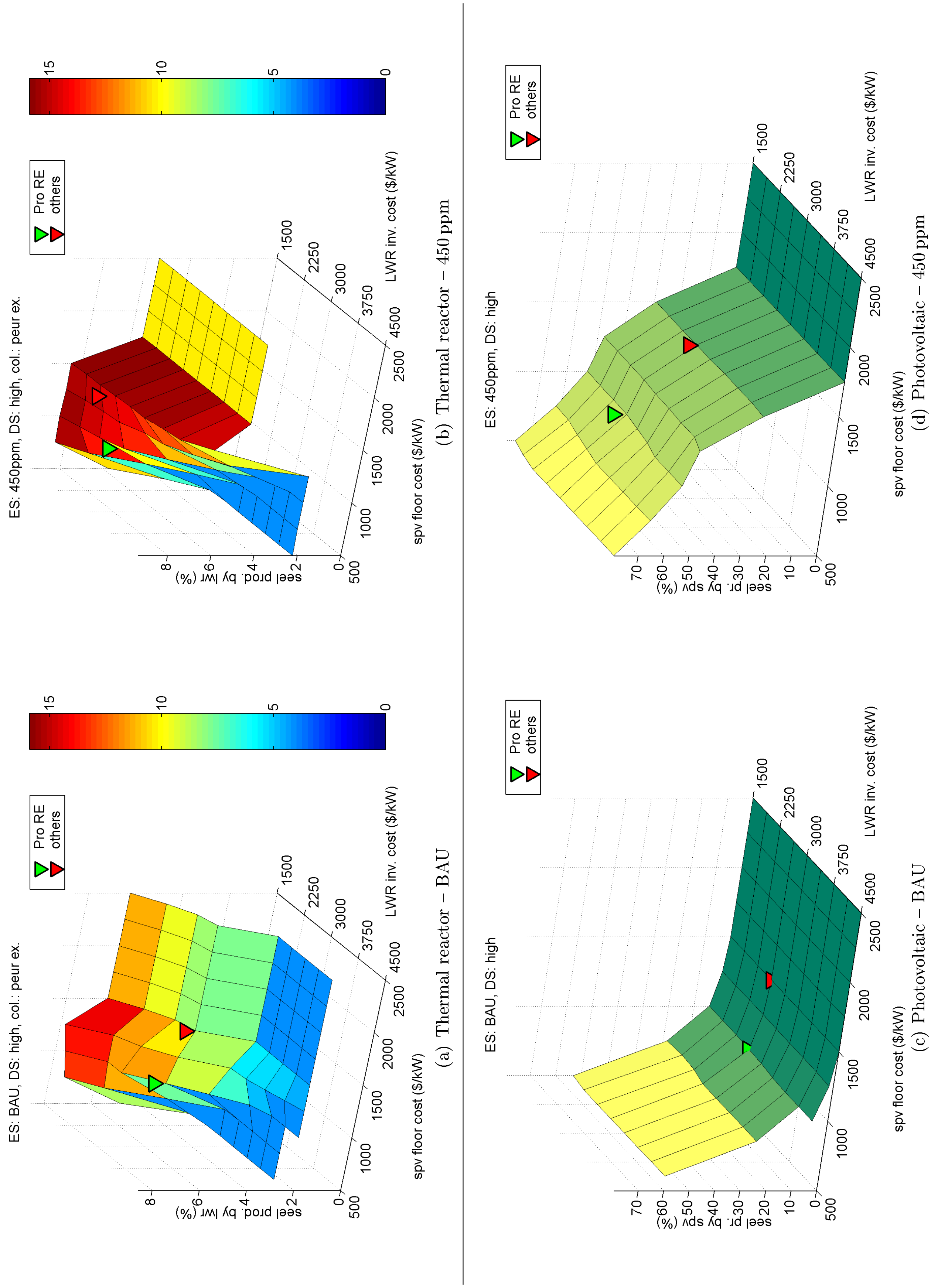


(a) Low fuel costs



(b) High fuel costs

Figure 3.15: *Floor costs of photovoltaic vs. investment costs of fast reactors:* Cumulated capturing of CO_2 (450 ppm scenario).



(a) Thermal reactor – BAU

(b) Thermal reactor – 450 ppm

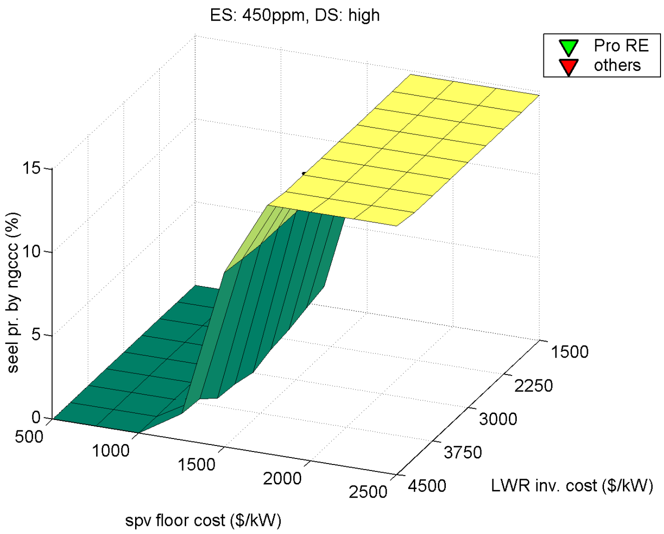
(c) Photovoltaic – BAU

(d) Photovoltaic – 450 ppm

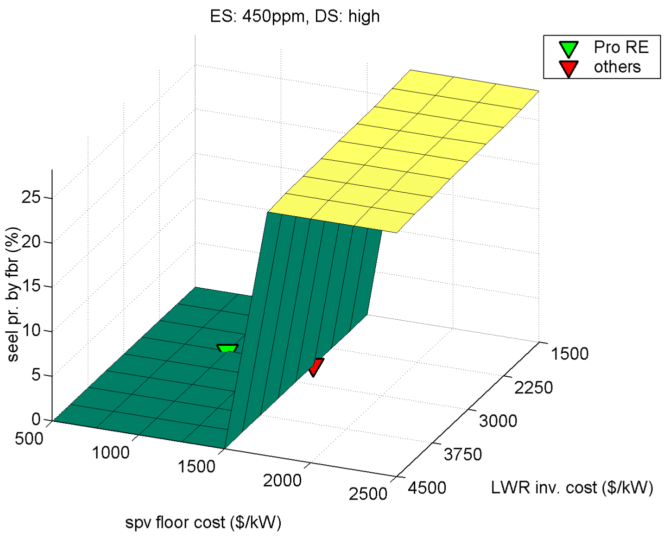
Figure 3.16: *Floor costs of photovoltaic vs. investment costs of thermal reactors:* electricity production of thermal reactors and photovoltaic (high demand).

- The share of photovoltaics drops down to zero under certain conditions, but the share of thermal reactors never drops below a value of 2.3 %. This values is still higher than electricity that is produced by operating the existing reactors until their lifetime has ended, without building new ones (which amounts to 1 %).

To evaluate the effects of not using the option of thermal reactors at all, the experiment was repeated with a forced phaseout of thermal reactors. This was realized by setting an upper constraint of zero on capacity additions of thermal reactors for all timesteps. Figure 3.18 shows (for the high demand scenario) the relative increase of the total energy system costs due to switching off the thermal reactor option. The cost increase varies between -1 – 2 % in the BAU scenario, and -1 – 5 % in the 450 ppm policy scenario. it is interesting to note that a negative cost increase occurs at all – which signifies that for certain parameter combinations not using thermal reactors is cheaper than using them.

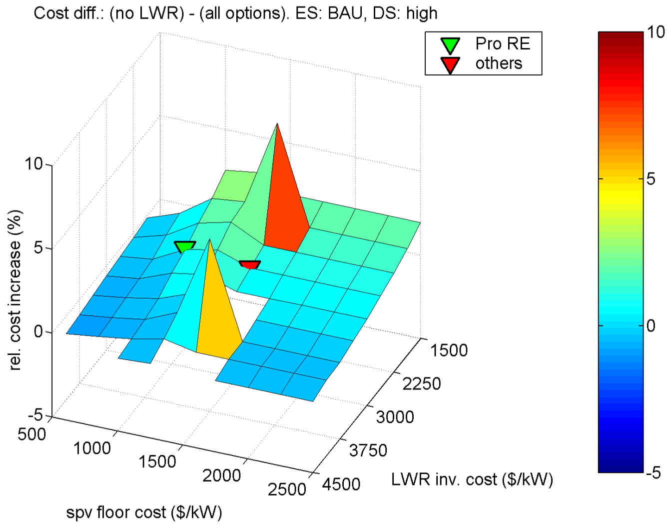


(a) Gas comb. cycle + CCS ppm

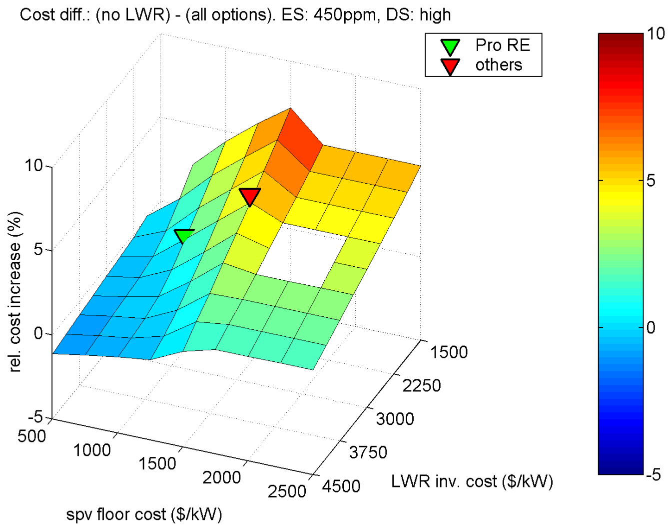


(b) Fast reactor

Figure 3.17: *Floor costs of photovoltaic vs. investment costs of thermal reactors:* Electricity production of gas combined cycle powerplants and fast reactors. These technologies benefit from an increase of photovoltaic floor costs and partially substitute thermal reactors when photovoltaic costs are very high. (450 ppm, high demand).



(a) BAU



(b) 450 ppm

Figure 3.18: *Floor costs of photovoltaic vs. investment costs of thermal reactors:* Relative increase of total energy system costs due to switching off the thermal reactor option (high demand).

Table 3.5: Floor costs of photovoltaic vs. learning rate of photovoltaic: choice of parameters.

Experiment parameters	Unit	Parameter range
Floor costs of SPV	$/kW	500 – 2500
Learning rate of SPV	%	0 – 32
Fossil fuel costs	-	high / low
Fast reactor option	-	on / off
Thermal reactor option	-	on / off

3.2.4 Floor costs of photovoltaic vs. learning rate of photovoltaic

During all experiments that were previously presented, a fixed learning rate for photovoltaic of 20 % was used while variing the floor costs. Of course it can be expected that not only the 'bottom line', but also the velocity of the cost reductions will affect the model results. During the following experiment, both parameters were varied simultaneously. Special attention will be given to the competition between photovoltaic and fast nuclear reactors, as the previous results indicate that the model tends to switch between solutions that use one, and only one, of these two technologies. To evaluate the 'value' of the nuclear option, the experiment has been repeated several times while switching fast and thermal reactors on and off together and individually, and the differences of the total energy system costs have been compared.

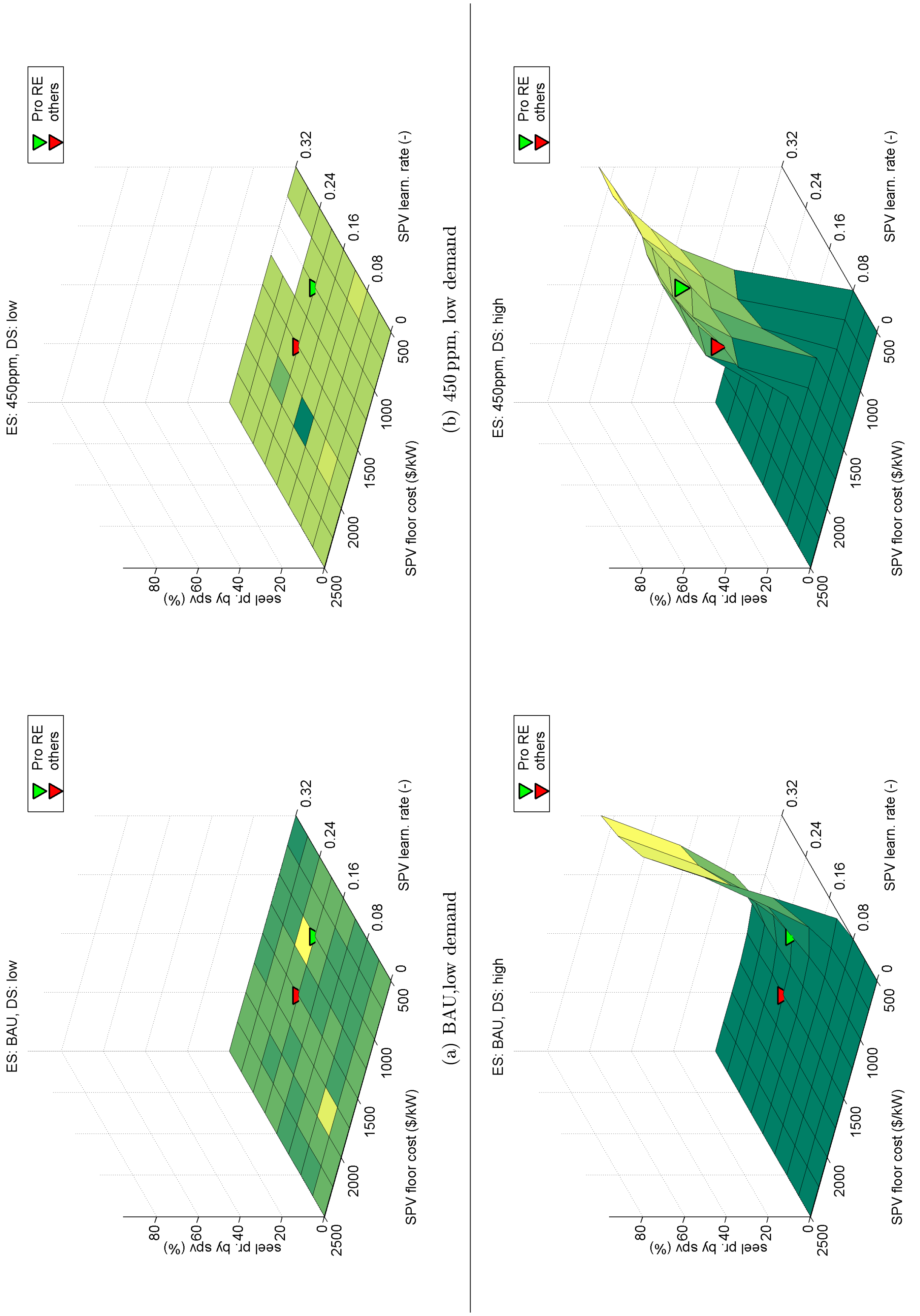
Table 3.5 shows the parameter ranges that were used. All other paramters are the same as in the *Fossil & RE* base case.

Shares of electricity production

Figures 3.19, 3.20, 3.21 and 3.22 show the cumulated share of electricity generation by photovoltaic and fast reactors, respectively. The results are presented for eight different cases, regarding all possible combinations of emission scenarios (BAU and 450 ppm), demand scenarios (high and low) and fossil fuel cost scenarios (high and low)[9]. All technology options were available. Several observation can be made:

- Again, the two technologies compete for the same habitat: they never occur together.
- Increasing the costs of fossil fuels gives an advantage to both technologies.
- In the BAU / low demand scenarios, both technologies are not used.
- In the 450 ppm/ low demand scenarios, photovoltaic is not used at all, and fast reactors have a constant share of 11 % and 28 % (low and high fossil fuel costs, respectively).

[9]Please note that the scaling of the vertical axes is not consistent as the results are taken from different experiments.



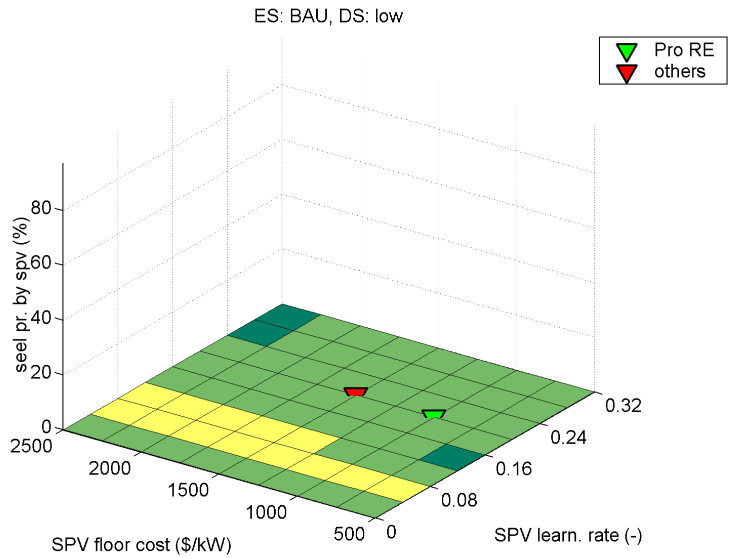
(a) BAU,low demand

(b) 450 ppm, low demand

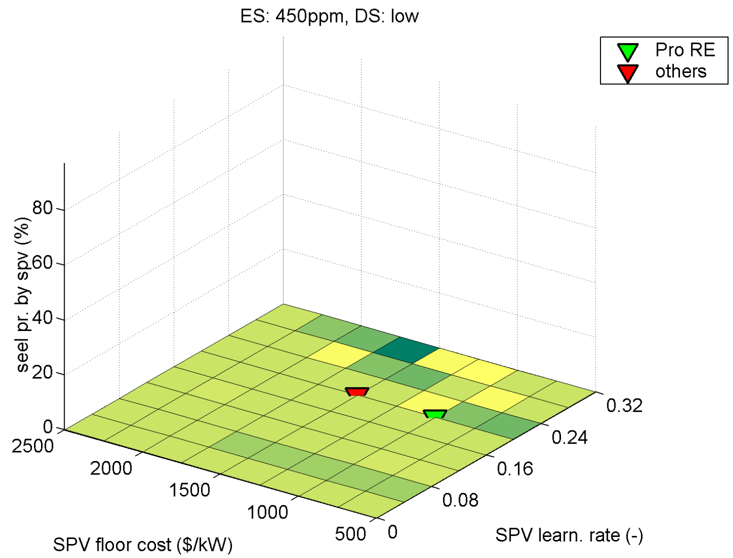
(c) BAU,high demand

(d) 450 ppm, high demand

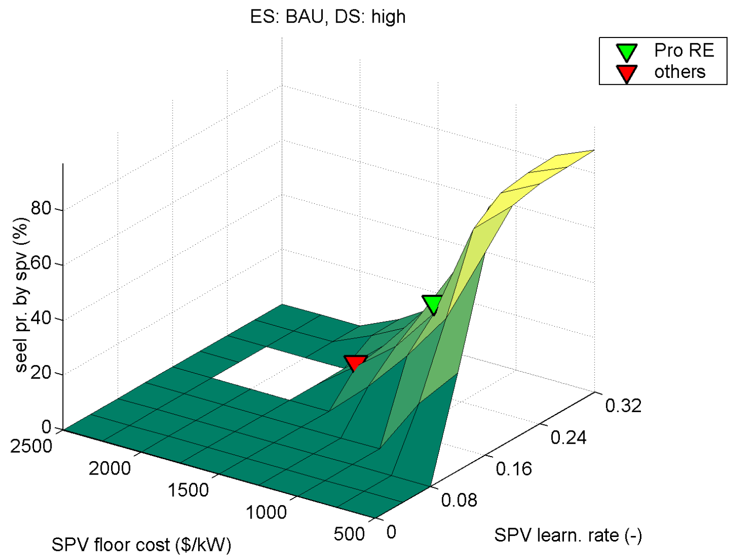
Figure 3.19: *Learning rate and floor cost of photovoltaic:* electricity production by photovoltaic (low fossil fuel costs).



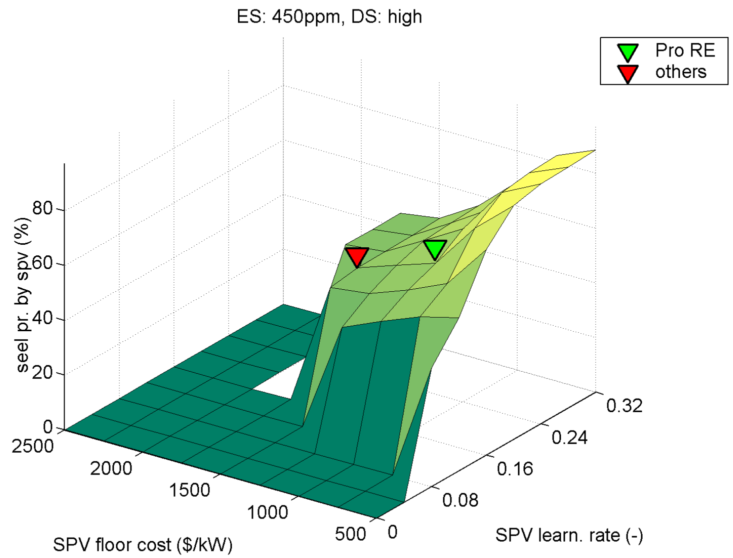
(a) BAU,low demand



(b) 450 ppm, low demand

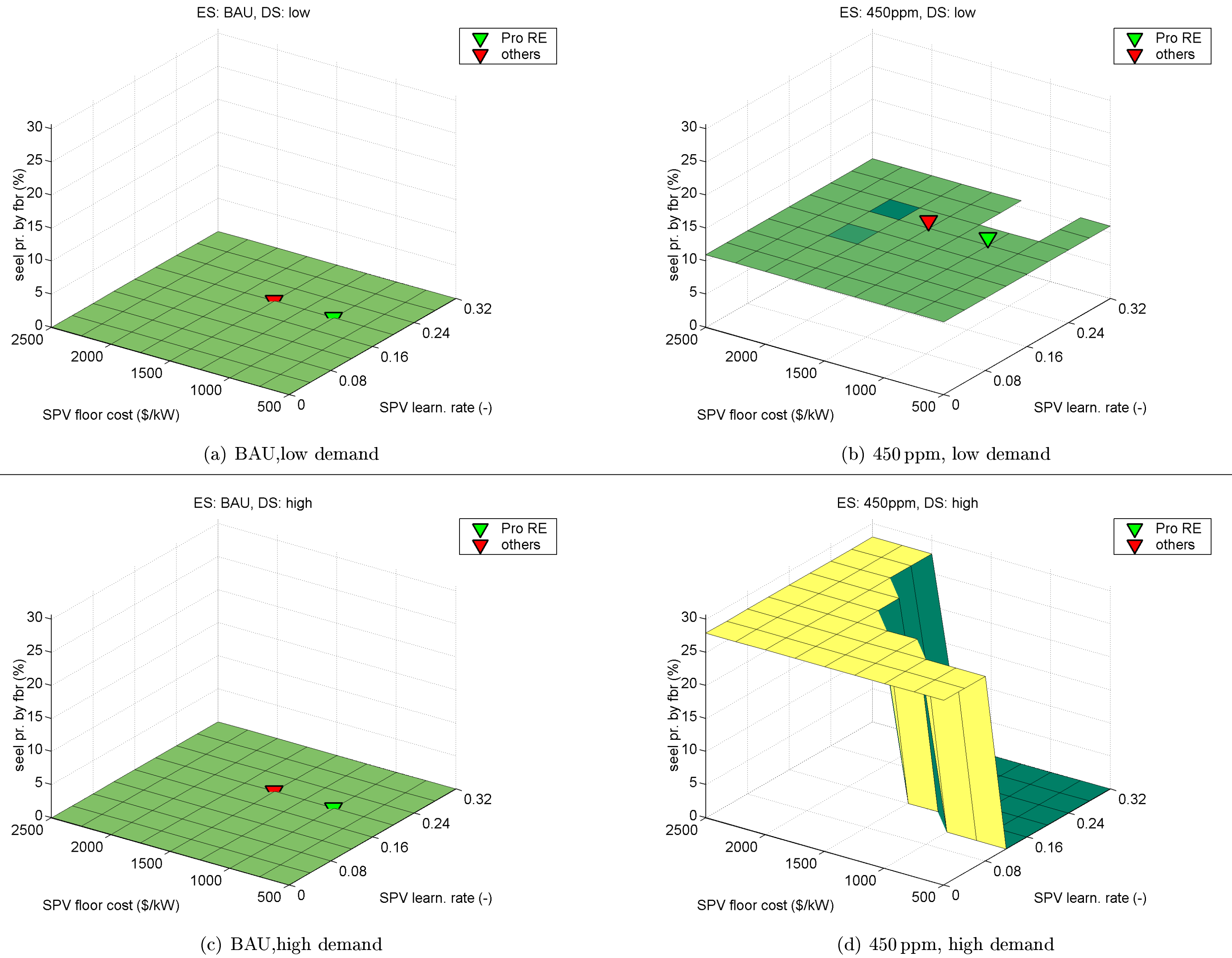


(c) BAU,high demand



(d) 450 ppm, high demand

Figure 3.20: *Learning rate and floor cost of photovoltaic*: electricity production by photovoltaic (high fossil fuel costs).



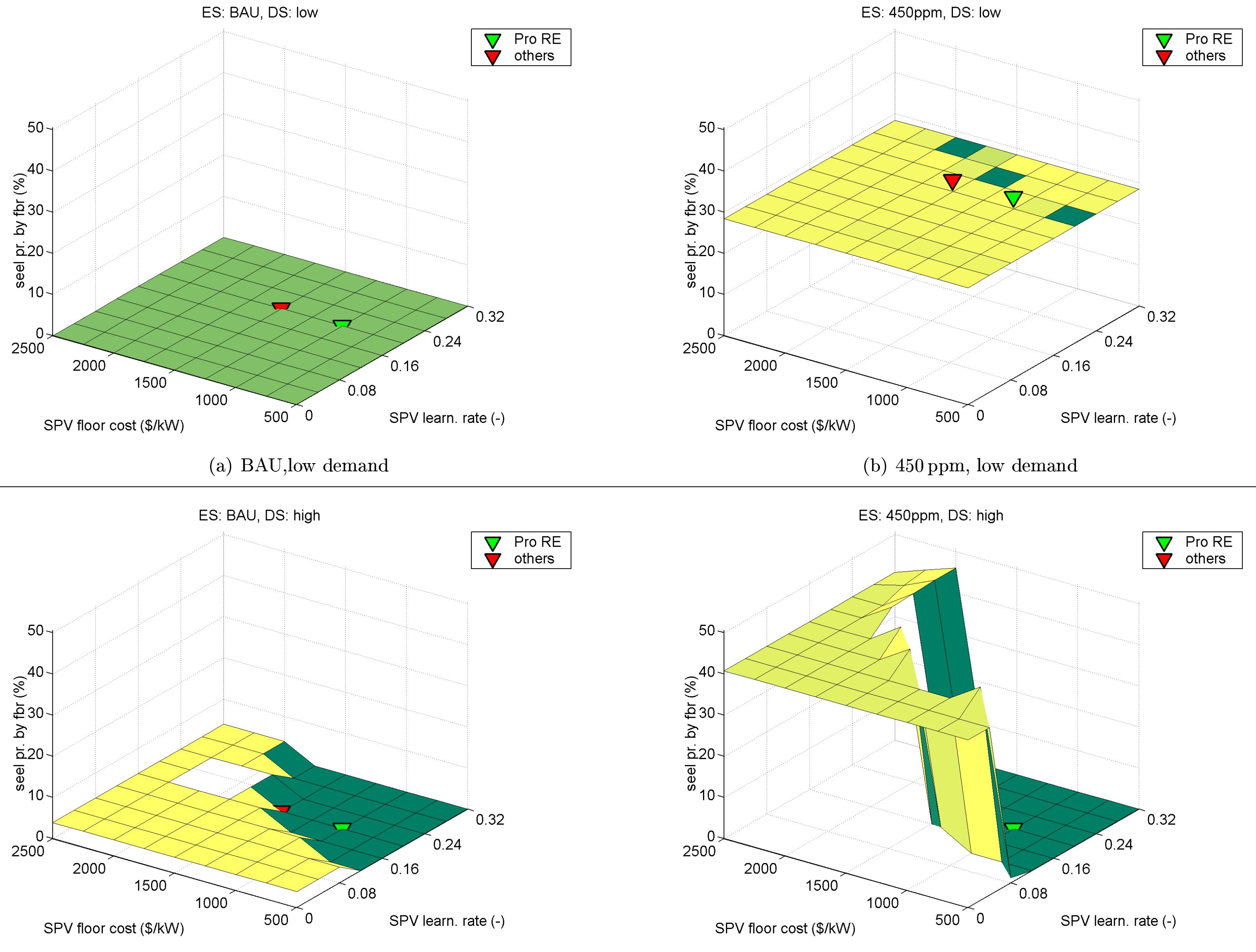
(a) BAU,low demand

(b) 450 ppm, low demand

(c) BAU,high demand

(d) 450 ppm, high demand

Figure 3.21: *Learning rate and floor cost of photovoltaic*: electricity production by fast reactors (low fossil fuel costs).



(a) BAU,low demand

(b) 450 ppm, low demand

(c) BAU,high demand

(d) 450 ppm, high demand

Figure 3.22: *Learning rate and floor cost of photovoltaic*: electricity production by fast reactors (high fossil fuel costs).

Mitigation costs and the value of technological options

This section examines how mitigation costs are affected by the influence of fossil fuel costs and the availability of nuclear energy technologies. The mitigation costs are defined as the difference between the (discounted) total energy system costs of the 450 ppm and the BAU scenario.

Figure 3.23 and 3.24 show the mitigation costs for different experiments. Each figure compares the following scenarios:

- All options available.
- Fast reactor switched off.
- Fast reactor and thermal reactor switched off.

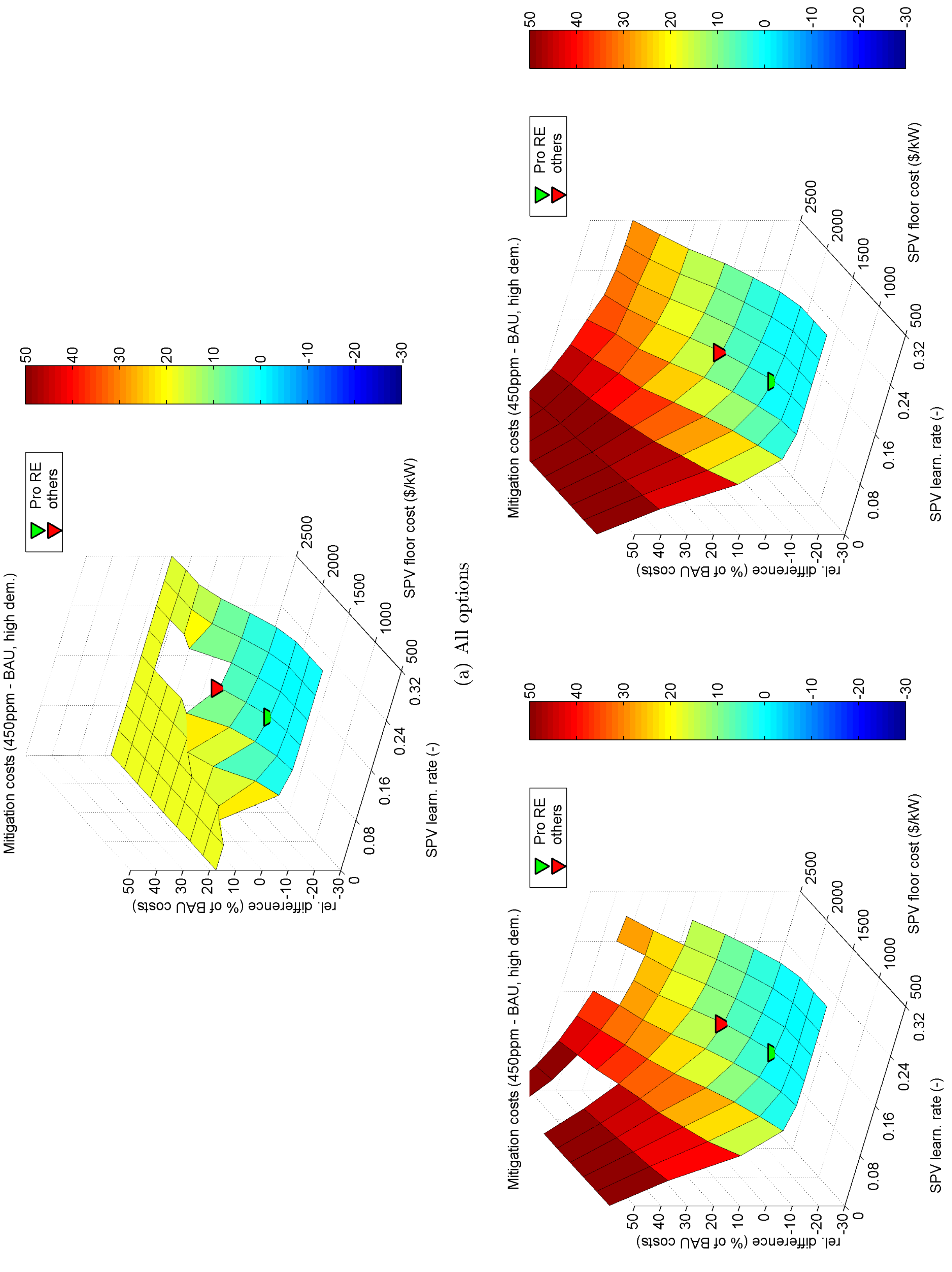
For the two figures, different fossil fuel cost scenarios were assumed (high and low for 3.23 and 3.24, respectively).

The following ovservations can be made:

- The mitigation costs vary considerably and are very sensitive to the learning parameters of photovoltaic for those model runs where photovoltaic is used. Where photovoltaic is not used, the mitigation reach a constant upper limit of 19 % and 36 % (high and low fossil fuel costs, respectively). For optimistic learning assumptions, there remains a parameter space where mitigation costs are 0 or close to 0 for all scenarios.
- If one or both nuclear reactor technologies are switched off, mitigation costs rise considerably in the parameter space where fast reactors would otherwise be used, and reach values of up to 75 %. However, in the parameter space where photovoltaic is cheap and fast reactors are not used even if they are available, mitigation costs are only marginally affected by the toggling of options. This, together with the fact that difference between switching off only fast reactors or both reactor types is quite small, indicates that the major part of the increase in mitigation costs can be attributed to the availability of fast reactors, whereas thermal reactors only play a minor role.
- Mitigation costs are also highly sensitive to the assumptions about fossil fuel costs. High fossil fuel costs decrease the level of the 'plateau' in the scenarios where all options are available. Also, they increase the parameter space where mitigation costs are below 5 % in the other scenarios.

Figures 3.25 and 3.26 compare the (discounted) total energy system costs between experiments where all options have been available with those where fast reactors or both reactor types were switched off. Only the 450 ppm policy scenario is presented. These values can be interpreted as the increase of mitigation costs due to not using fast reactors or both nuclear reactor types.

Several observations can be made:

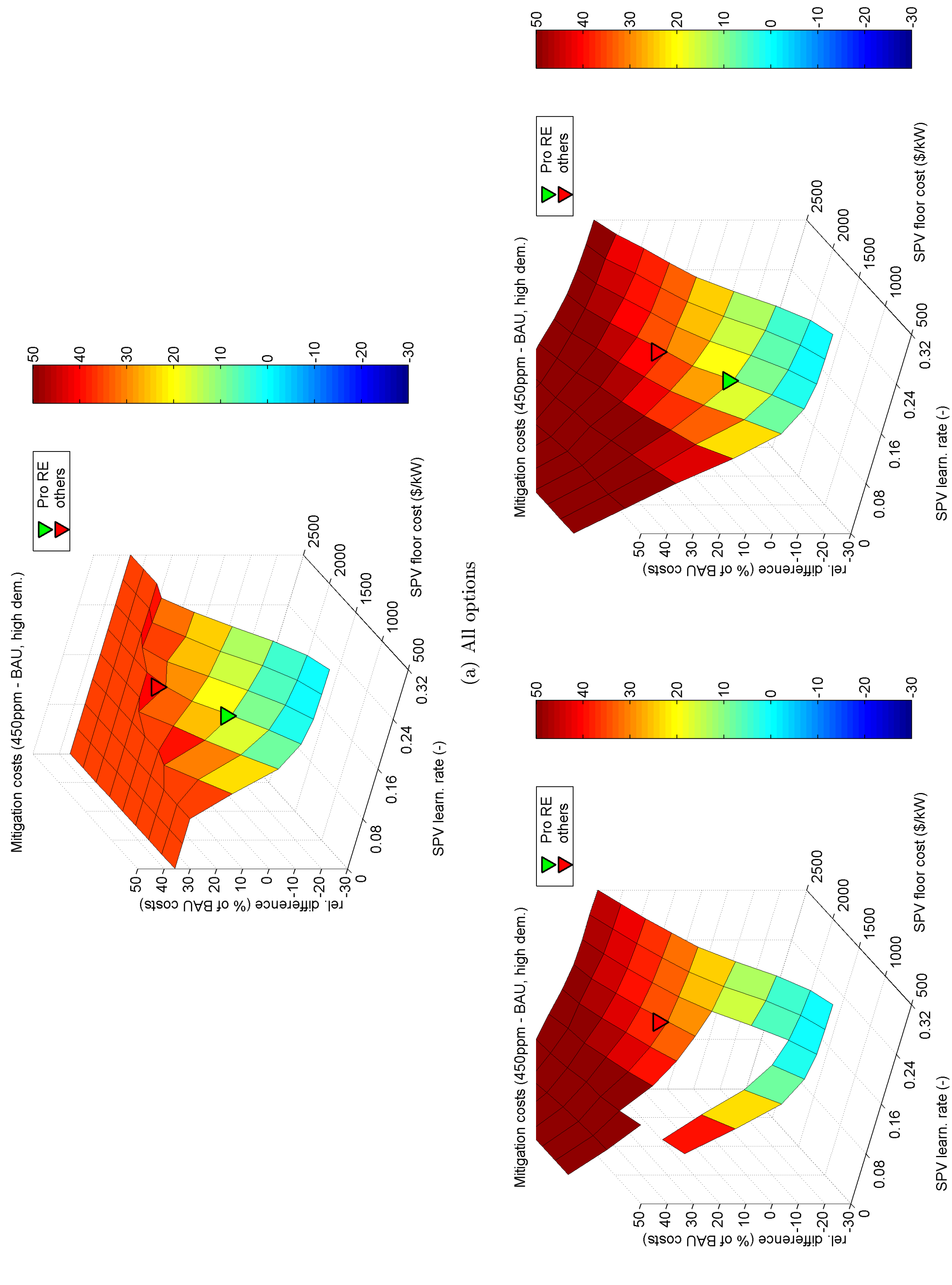


(a) All options

(b) No fast reactor

(c) No fast & thermal reactors

Figure 3.23: *Learning rate and floor cost of photovoltaic:* Mitigation costs with and without the option of nuclear reactors (high demand, high fossil fuel costs).



(a) All options

(b) No fast reactor

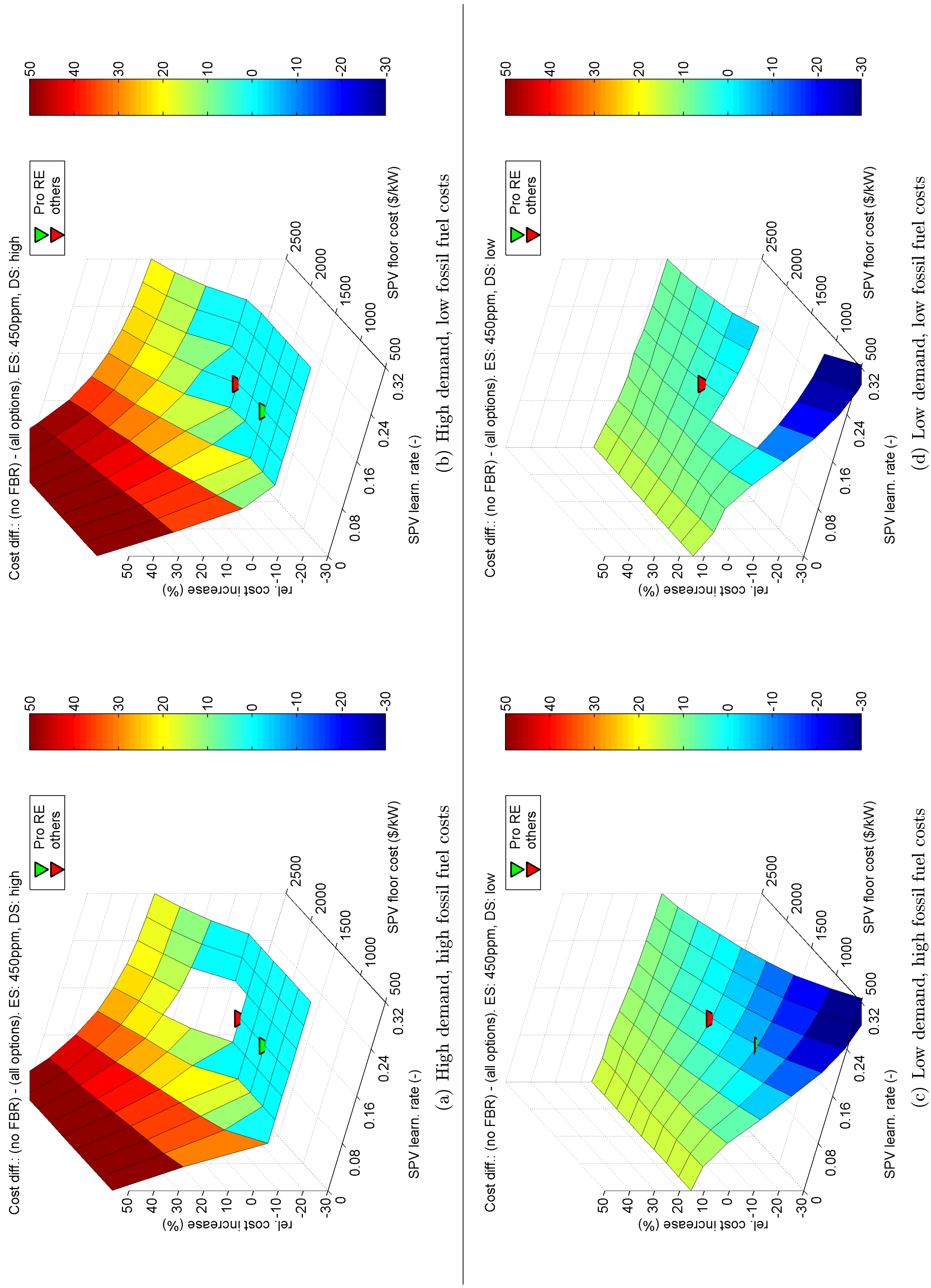
(c) No fast & thermal reactors

Figure 3.24: *Learning rate and floor cost of photovoltaic:* Mitigation costs with and without the option of nuclear reactors (high demand, low fossil fuel costs).

- The high demand case, not surprisingly, shows considerable cost differences in the parameter space where photovoltaic is expensive and the fast reactor option is used when it is available.
- The cost increase due to switching off fast reactors reaches a plateau of 0 in the parameter space where fast reactors would not be used even it was switched on.
- In the same parameter space, when both nuclear options are turned off, a cost increase can be observed – which is due to the fact that thermal reactors would be used in this space if they were allowed. However, this cost increase is quite low (between 0 and 7 %).
- The mitigation cost increase due to switching off any nuclear option is fairly independent of the fossil fuel cost scenario. That is quite interesting, as effect of fossil fuel costs on the *absolute* mitigation costs is quite substantial. But as these affects are similar in all scenarios, regardless of the availability of nuclear technologies, they outweigh each other when a cost difference between two scenarios is calculated. The option value of nuclear energy is not dependent on the price of fossil fuels, but it is crucially dependent on the economics of renewable energy sources.

The low demand case does show a surprising result: Switching off one or both nuclear technologies results in substantial net benefits!

For comparison, figure 3.27 shows the same cost difference, but this time calculated for the complete time horizon (2005–2150 instead of 2005–2100) to test if these benefits are caused by end effects. The result pattern is equal to the one presented above. Obviously, in this scenario there exist two local optima, one with a significant share of fast reactors and one without them, and the one without them has the lower total costs.



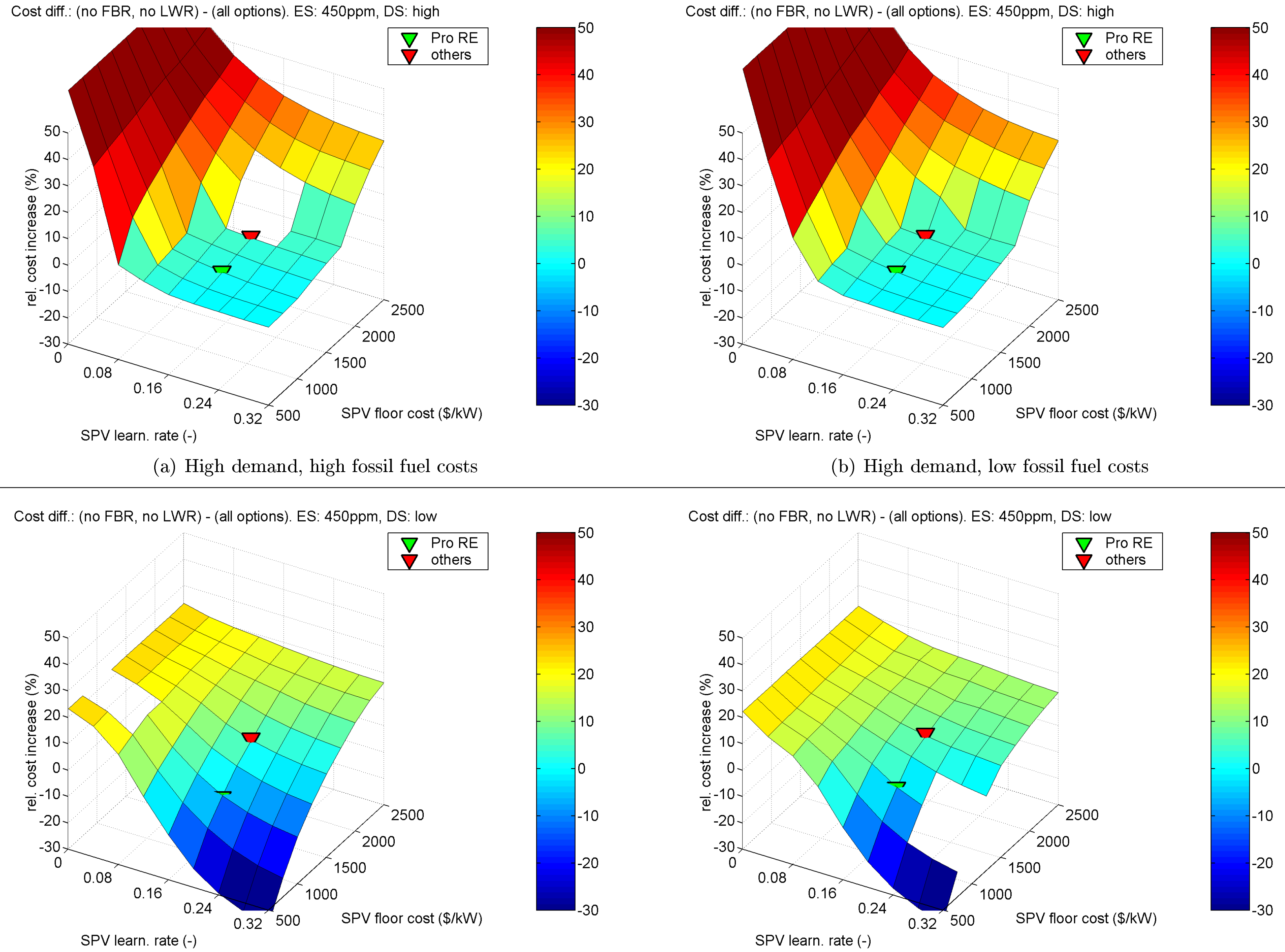
(a) High demand, high fossil fuel costs

(b) High demand, low fossil fuel costs

(c) Low demand, high fossil fuel costs

(d) Low demand, low fossil fuel costs

Figure 3.25: *Learning rate and floor cost of photovoltaic:* Increase of total energy system costs due to switching off fast reactors (FNR) (450 ppm).



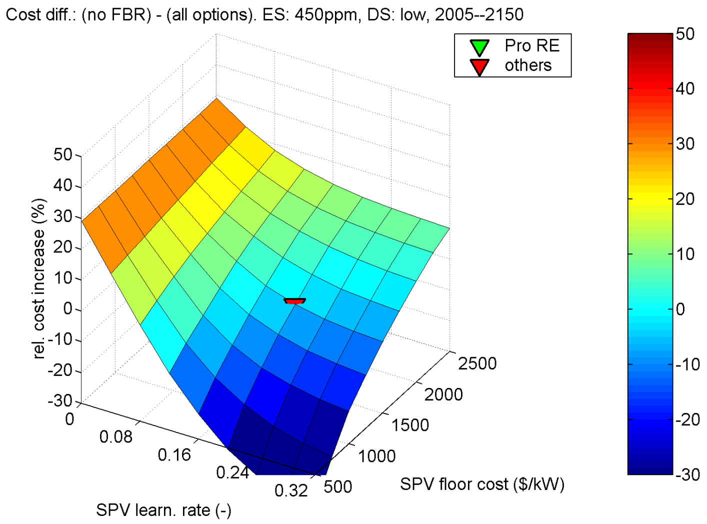
(a) High demand, high fossil fuel costs

(b) High demand, low fossil fuel costs

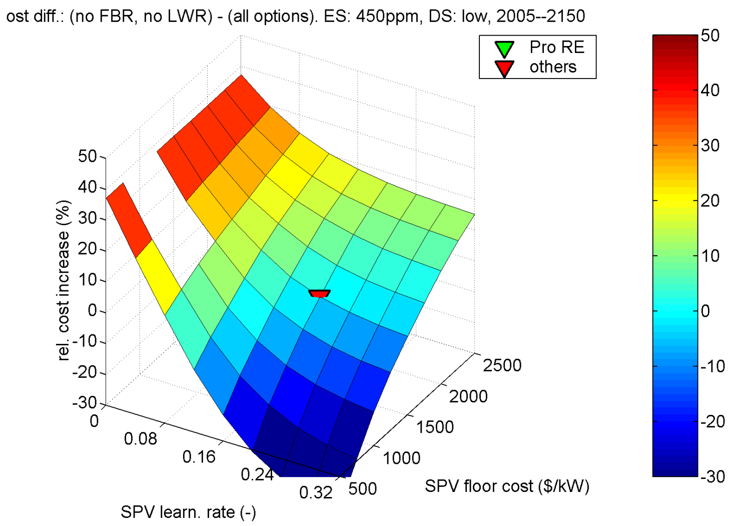
(c) Low demand, high fossil fuel costs

(d) Low demand, low fossil fuel costs

Figure 3.26: *Learning rate and floor cost of photovoltaic:* Increase of total energy system costs due to switching off fast reactors (FNR) and thermal reactors (TNR) (450 ppm).



(a) Low demand, high f. f. costs, no FNR



(b) Low demand, high f. f. costs, no FNR & TNR

Figure 3.27: *Learning rate and floor cost of photovoltaic:* Increase of total energy system costs due to switching off fast reactors (FNR) and / or thermal reactors (TNR) (450 ppm. 'f.f.costs' stands for 'fossil fuel costs'.). This figure calculates the costs over the complete time horizon (2005–2150) to check if the net benefits are caused by end effects.

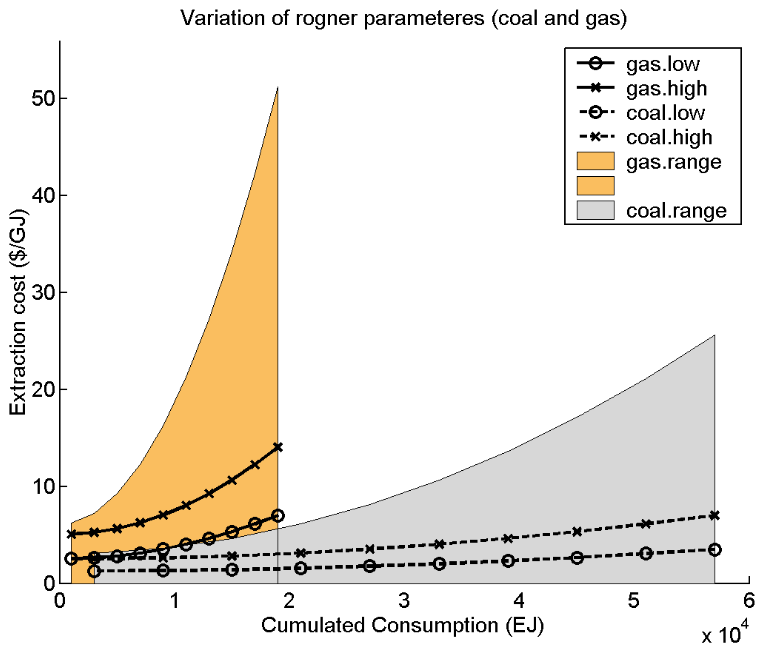


Figure 3.28: *Fossil fuel costs:* Variation of Rogner curve parameters.

3.2.5 Fossil fuel costs

During the following experiment the the extraction cost of the fossil fuels coal and gas have been varied. As a baseline, the low fossil fuel cost scenario was used. The initial costs χ_1 and the cost difference between highest and lowest point of the extraction curve χ_2 of this scenario have been scaled for gas and coal simultaneously (see eq. 3.1).

Figure 3.28 shows the range of cost / extraction curves that were used during the experiment[10]. As the uncertainty about the 'higher end' of the extraction curve is greater than for the 'lower end', the parameter range for χ_2 was chosen generously, and the cost increase significantly surpasses the one assumed for the two base scenarios.

$$\begin{aligned} \chi_{1,\text{ex}}(\text{coal}) &= p_1 \cdot \chi_{1,\text{base}}(\text{coal}) \\ \chi_{1,\text{ex}}(\text{gas}) &= p_1 \cdot \chi_{1,\text{base}}(\text{gas}) \\ \chi_{2,\text{ex}}(\text{coal}) &= p_2 \cdot \chi_{2,\text{base}}(\text{coal}) \\ \chi_{2,\text{ex}}(\text{gas}) &= p_2 \cdot \chi_{2,\text{base}}(\text{gas}) \end{aligned} \tag{3.1}$$

Index 'base':	Rogner curve parameters of the low fossil fuel cost scenario
Index 'ex':	Rogner curve paramters in the multi-run experiment
p_1, p_2:	Experiment parameters

Figure 3.29 shows the mitigation costs (low demand) and the cumulated amount of sequestrated CO_2 (low demand / 450 ppm scenario). As expected, the mitigation costs are sensitive to both experiment parameters. The cumulated CO_2 sequestration, however,

[10] See section 2.5.4 for a description of the fossil fuel cost scenarios that were used in this study.

Table 3.6: *Fossil fuel costs*: Choice of parameters

Experiment parameters	Unit	Parameter range
χ_1 scaling factor (p_1)	-	0 – 2.4
χ_2 scaling factor (p_2)	-	0 – 10
χ_1(gas) resp. χ_1(coal)	$/GJ	0 – 6 resp. 0 – 3
χ_2(gas) resp. χ_2(coal)	$/GJ	0 – 56 resp. 0 – 28

is much more sensitive to variation of χ_1 (the initial base costs of fossil fuels). If the χ_1 scaling parameter surpasses a value of 1.2[11], CCS is not feasible at all.

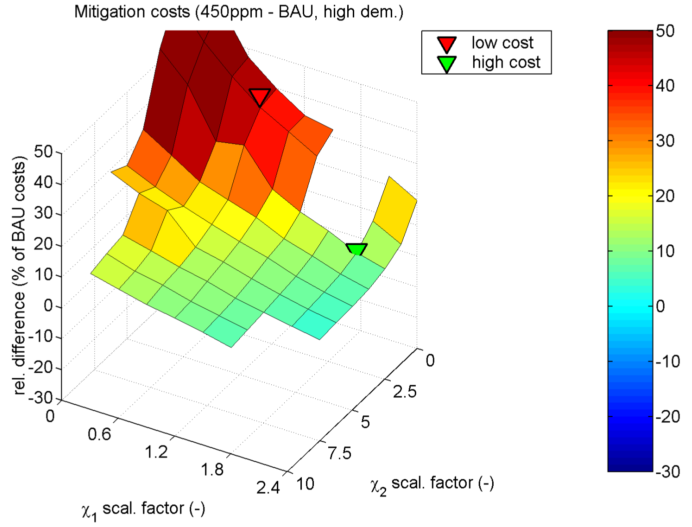
Figure 3.30 shows the electricity production shares for the two available CCS technologies (gas combined cycle with CCS and coal with CCS). The use of the coal + CCS option depends mainly on the initial fuel costs χ_1), while the use of gas + CCS depends on the cost increase due to scarcity (χ_2) as well. This reflects the fact that the resource base of gas is much smaller than that of coal. The gas + CCS option is only used if the increase of gas extraction costs is fairly moderate.

Figure 3.31 shows the cumulated consumption of coal and gas, comparing BAU and policy scenario. The upper limit of the vertical axis is also the upper limit of the available resources. It shows the considerable decrease of coal consumption due to implementing an emission cap. It also shows that in the BAU case, so much coal is consumed that the cost increase χ_2) of coal begins to affect its use.

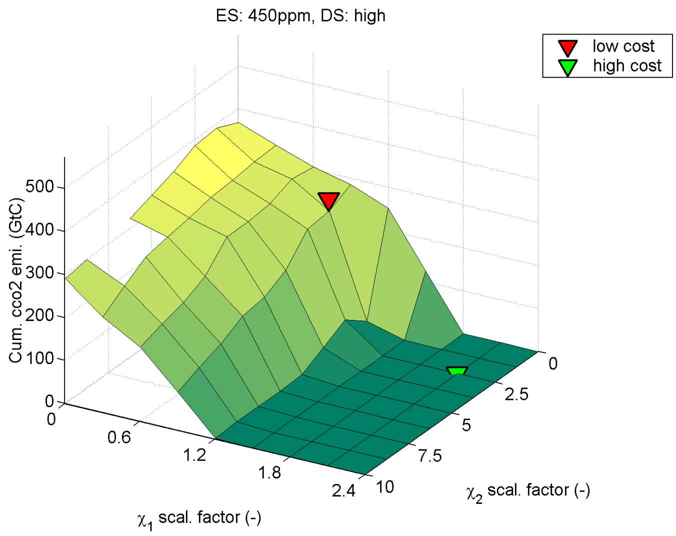
Figures 3.32 and 3.33 shows the electricity production by non-CCS technologies (high demand scenario)[12]. The feasibility of renewable energy technologies (wind and photovoltaic) increases with the projected fossil fuel costs and is furthermore pushed forward by applying an emission costraint. Interestingly, the share of thermal reactors decreases with increasing χ_2 values. There seems to be a competition between a combination of CCS and thermal reactors on one hand and a combination of renewable energy sources on the other hand. Fast reactors are not used at all. The decision whether to choose fast reactors or photovoltaic as a 'backstop' technology depends on the cost parameters for those two technologies (see previous sections). Obviously this choice is rather independent of fossil fuel costs.

[11] Which equals initial fuel costs of χ_1(gas) = 3 $/GJ and χ_1(gas) = 1.5 $/GJ.

[12] Please note that viewpoint is different than in figures 3.29, 3.30 and 3.31.

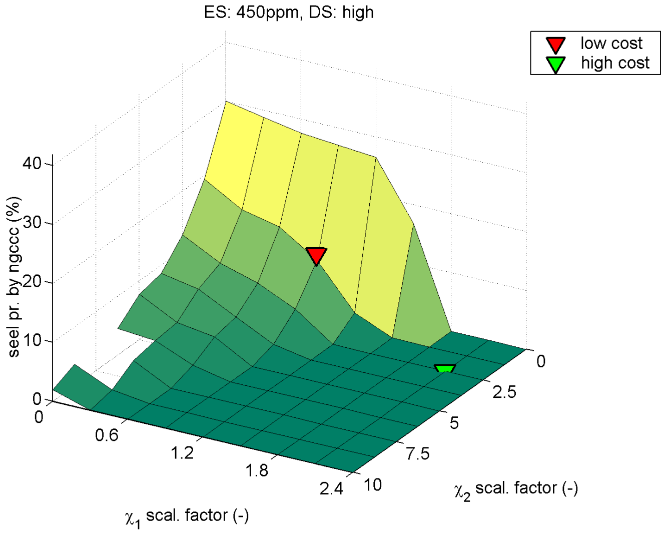


(a) Mitigation costs

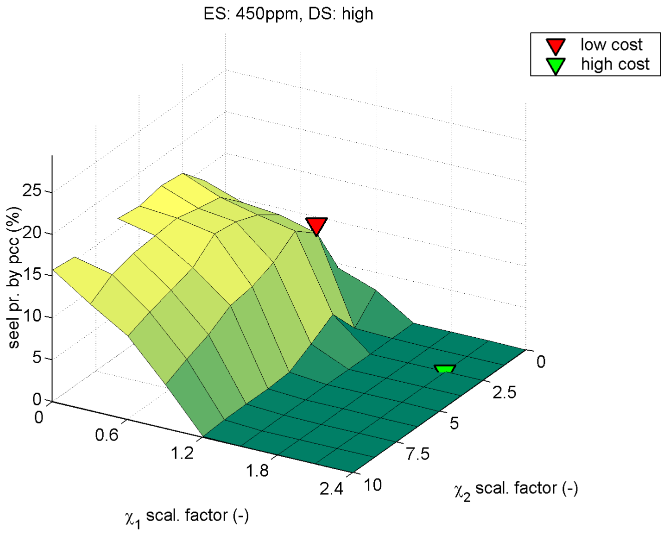


(b) CO_2 sequestration (450 ppm)

Figure 3.29: *Fossil fuel costs:* Mitigation costs and cumulated CO_2 sequestration (high demand).



(a) Gas comb. cycle / CCS



(b) Coal / CCS

Figure 3.30: *Fossil fuel costs:* Electrity production by CCS technologies (high demand, 450 ppm).

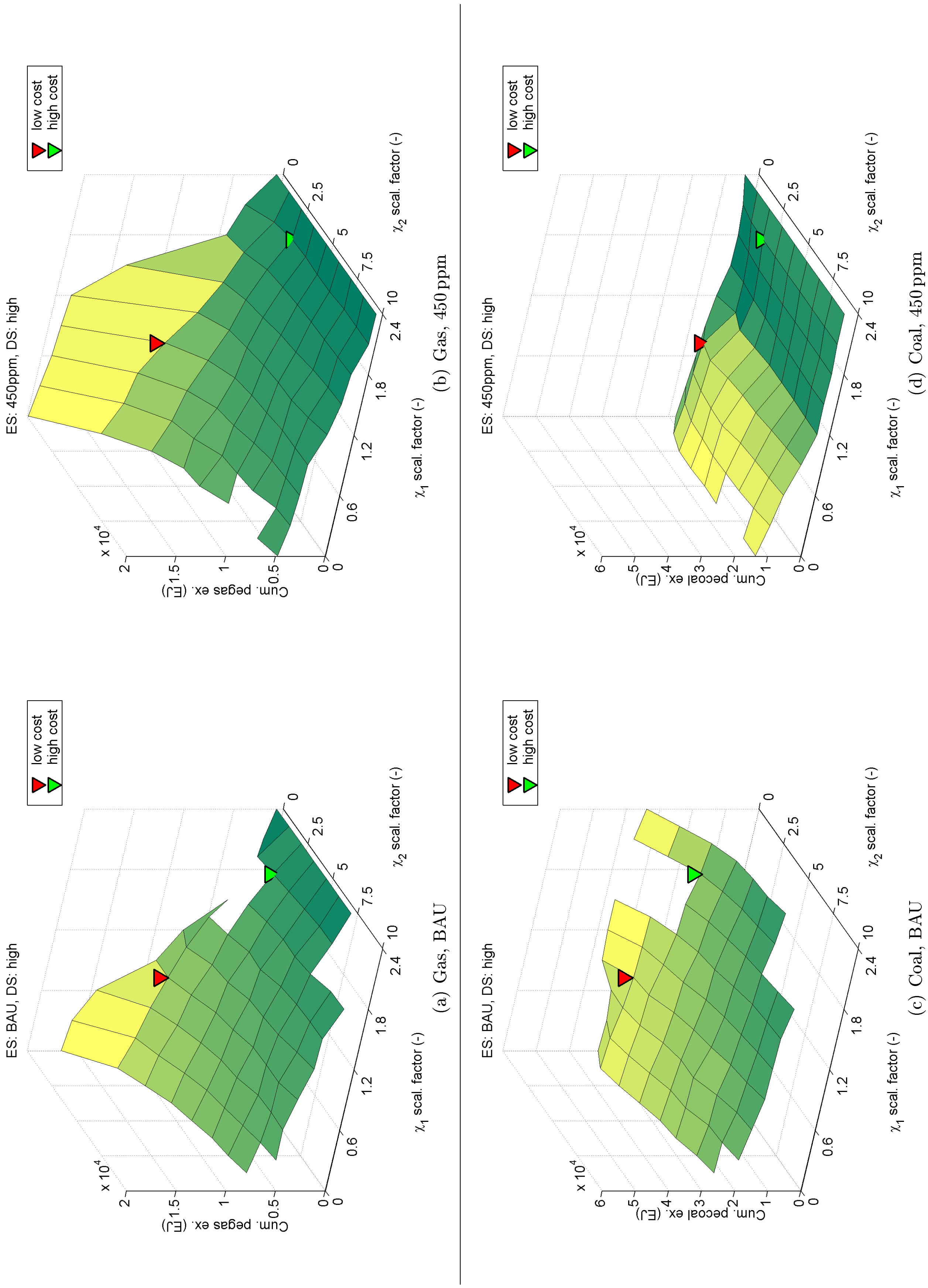
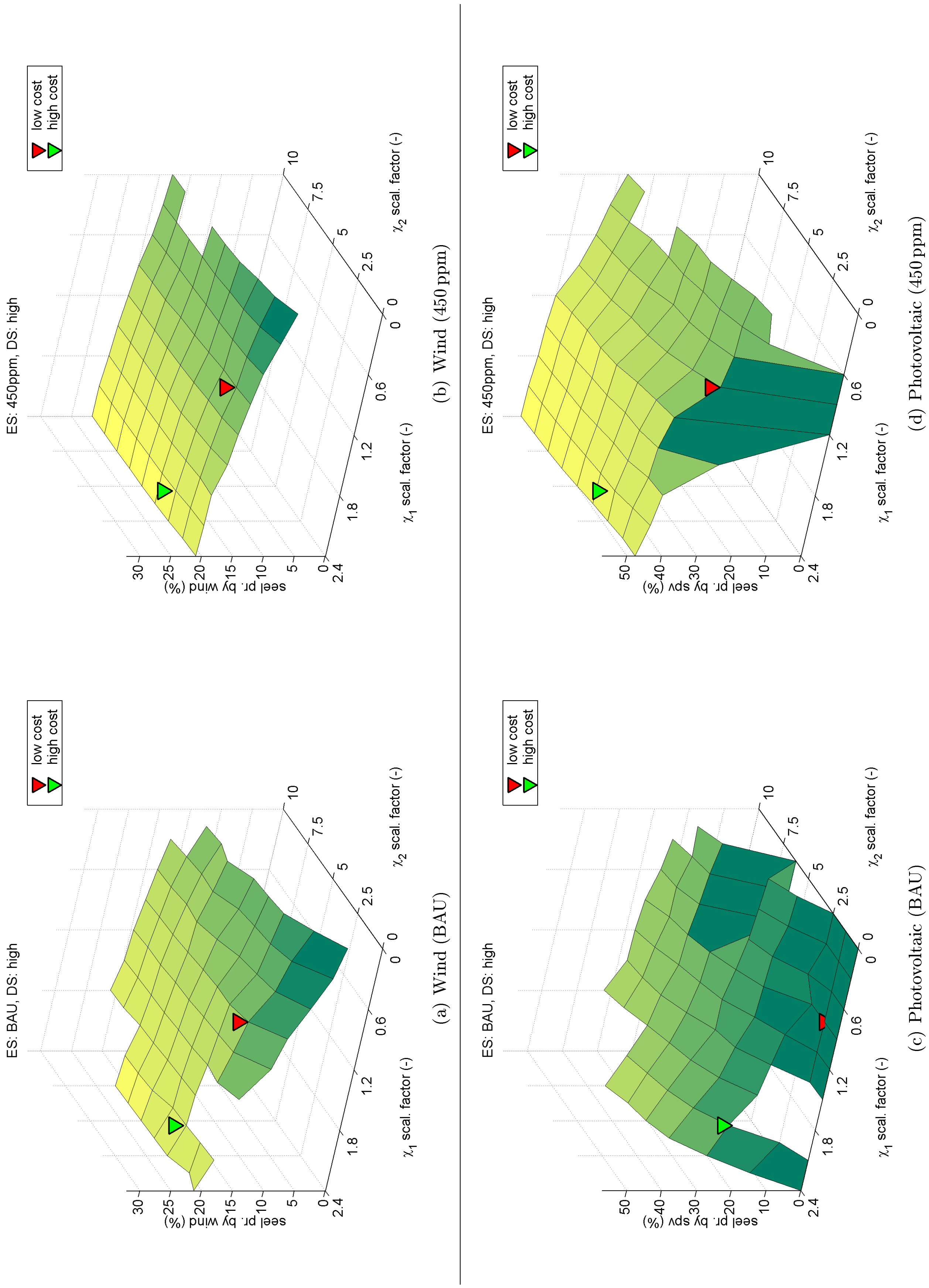


Figure 3.31: *Fossil fuel costs:* Cumulated gas and coal consumption (high demand).



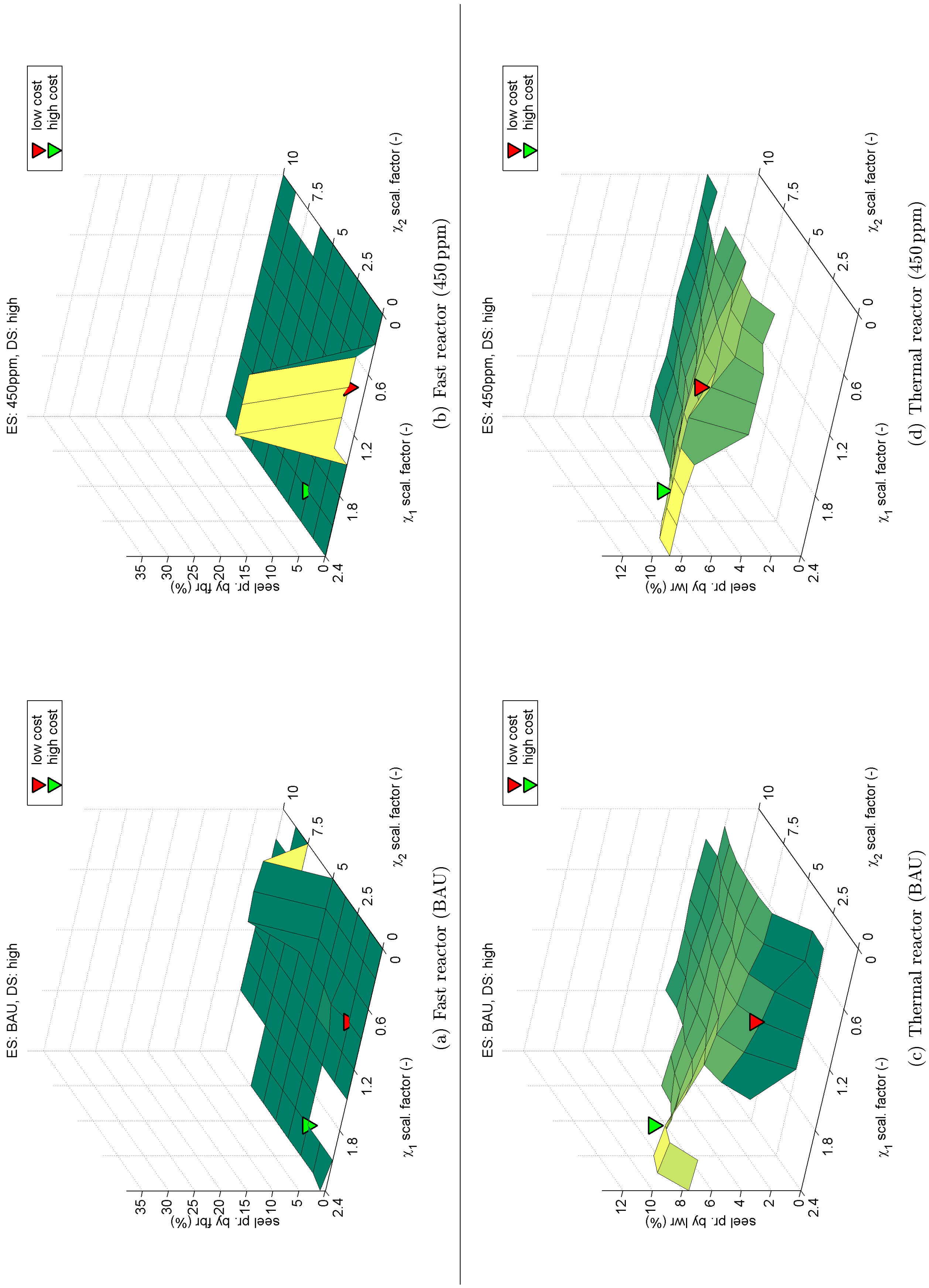
(a) Wind (BAU)

(b) Wind (450 ppm)

(c) Photovoltaic (BAU)

(d) Photovoltaic (450 ppm)

Figure 3.32: *Fossil fuel costs:* Electrity production by nuclear reactors (high demand, 450 ppm).



(a) Fast reactor (BAU)

(b) Fast reactor (450 ppm)

(c) Thermal reactor (BAU)

(d) Thermal reactor (450 ppm)

Figure 3.33: *Fossil fuel costs:* Electrity production by wind and photovoltaic (high demand, 450 ppm).

4 Conclusions

4.1 Summary of results

I will give a summary of the main findings, loosely ordered by the mitigation options the can be appointed to. Due to the nature of the results there will be a focus on the competition relationship between fast reactors and photovoltaic.

Fossil fuels and CCS

Fossil fuels without Carbon Capture are used widely if no emission restrictions apply. This is especially true for coal. In the presence of emission constraints, the use of coal and gas without carbon Capture is necessarily restricted. The use of CCS is highly sensitive to fossil fuel costs. CCS is always used together with a mix of various technologies – and its maximum share of total electricity generation is limited due to the strictness of the emission constraint, especially at the end of the century.

The results indicate that the development of fossil fuel prices have a strong impact on the *costs* of mitigation. Their impact on the choice of non-fossil *alternatives*, and also on the *economic value* of different technological options, is much less significant.

Thermal nuclear reactors

Under most parameter assumptions, especially if a cap on emissions exist, the thermal reactor option is used, although it's maximum share is constricted by the limited uranium resources. As this maximum share is fairly small, the increase in mitigation cost due to not using this technological option are relatively small as well.

Fast nuclear reactors and photovoltaic

The study shows a remarkable similarity of the role, the potential, and the behaviour of fast reactors and photovoltaic. While the physical potential of both technologies is certainly limited, these limitations are so weak that they are not binding – at least in the chosen modeling approach and time horizon. Therefore they compete for the role of a backstop technology that will be introduced in the second half of this century and dominate the electrity sector after the substitution of fossil fuels has taken place.

An important result is that the two options only compete with each other – neither thermal reactors nor CCS have the potential to assume their position. The choice between either option depends on the economic parameters for both of them – and these parameters are associated with significat uncertainties.

What can be said is that in the range of paramter assumptions that was explored in this study, scenarios to the favour of both technologies exist.

The possibility is high that a future without nuclear power is possible – the potential of renewable energy sources is high enough, under both physical *and* economical aspects. On the other hand, a future based on nuclear energy, without using the renewable energy option, seems possible as well, at least in the electricity sector. It also seems – and this is a very important conclusion – that a combination of both possibilities, a future in which both option coexist, is rather unlikely.

Closing remarks

This study was based on the assessment of the economical value of technological options. The results show both the advantages as well as the limitations of this approach. They indicate that from an economical point of view, nuclear and renewable energy could be regarded as *equal rivals*.

On the one side, supporters of the nuclear option who insist that renewable energy may well have the physical, but not the economical potential to satisfy future energy demands might soon run out of arguments. The same statement is true for the other side. Under the given parameter uncertainties it would be unwise to make a decision for either nuclear or renewable energy sources that is based purely on economic arguments.

A comprehensive assessment of all options that takes into account other than economical criteria was not the objective of this work. This will be left to further studies which should, apart from the question of economics, also assess the operational risks of nuclear reactors as well as the issues of waste disposal and proliferation.

4.2 Recommendations

The model results indicate that in the range of uncertainties (which is considerable) either the nuclear option or the renewable option (represented by fast reactors and photovoltaic) has an advantage from the economical point of view. This leads to the conclusion that future efforts should aim at decreasing the range of uncertainty. If more detailed statements are desired, it is crucial to assess the learning capacities and potential restrictions of renewable energy technologies on the one hand, and the true economic costs (especially by internalizing external effects that have not yet been regarded) of nuclear technologies on the other hand. The parametrization of these options, as it has been performed in this study, is far from complete.

There are already plans regarding the near future of the genEris tool and the energy system model that was designed with it: It will be integrated in a regionalized integrated assessment model called REMIND that couples the energy system with a macroeconomical growth model and a carbon cycle model. The regionalization will help to specify the geographical potential of renewable energy sources.

A Appendix

A.1 Nomenclature

This section gives an overview of the symbols and abbreviations that are used in this document. It is structured as follows:

- Mathematical symbols
  - Variables
  - Parameters
  - Sets and subsets
  - Mappings
- Abbreviations
  - Abbreviations for technologies
  - Abbreviations for energy types and quantities
  - Abbreviations for equations
- Units

Table A.1: Variables

Symbol	Arguments	Explanation
C_{FU}	t	fuel costs
C_I	t	investment costs
C_O	t	operation & maintenance costs
D_p	t, e_p, e_s, T	demand of primary energy of type e_p that is delivered to secondary energy type e_s through technology T
D_{p,η_c}	t, e_p, e_s, T_{η_c}	demand of primary energy - contribution of technologies with constant η
$D_{p,\eta(t)}$	$t, e_p, e_s, T_{\eta(t)}$	demand of primary energy - contribution of technologies with variable η
D_s	t, e_s, e_{out}, T	demand of secondary energy of type e_s that is delivered to energy type e_{out} ($e_{s'}$ or e_f) through technology T
F	t, e_x, g	fuel extraction of an exhaustible resource e_x of grade level g
K	t, T, g	capacity of energy or CCS transformation through technology T of grade level g
ΔK	t, T, g	addition to the capacity of technology T of grade level g
K_{cum}	t, T_L	cumulated capacity of a learning technology T_L
P_p	$t, e_p, e_s, T,$	production of primary energy of type e_p and grade level g that is delivered to secondary energy type e_s through technology T
P_s	t, e_{in}, e_{out}, T	production of secondary energy of type e_{out} (e_s or $e_{s'}$) that is delivered from energy type e_{in} (e_p or $e_{s'}$) through technology T
P_f	t, e_s, e_f, T	production of final energy of type e_f that is delivered from secondary energy type e_s through technology T
R	$t, y_i^{ccs}, y_{i+1}^{ccs}, T, g$	amount of CO_2 in the ith step of the CCS chain to be transformed to the next one using technology T with grade level g
S	t, s	amount in stock of quantity s
ΔS	t, s	change per time in stock of e_s if e_s is a stockable quantity
Y	t, e_{in}, e_{out}, T, y	amount of emissions from type y produced by conversions explained in $M_{T\rightarrow Y}$
$Y_{p\rightarrow s}$	t, e_{in}, e_{out}, T, y	share of Y from primary to secondary energy transformation
$Y_{s\rightarrow f}$	t, e_{in}, e_{out}, T, y	share of Y from secondary to final energy transformation
Y_{CCS}	t, e_{in}, e_{out}, T, y	share of Y from CCS
Z	$-$	discounted total energy system costs *(objective function)*

Table A.2: Sets and subsets

Symbol	Explanation
T	technology (energy transformation technology in general)
T_L	technology which develops through learning
T_{no-L}	technology which does not develop through learning
T_{ren}	renewable energy transformation technologies
e_p	primary energy type
e_s	secondary energy type
e_f	final energy type
e_x	exhaustible energy type
e_{in}	(general:) energy type entering a transformation
e_{out}	(general:) energy type resulting from a transformation
y	emission type
g	grade level
s	stockable quantity
t	time
t_l	life time
t_{su}	spin-up time period

Table A.3: Parameters

Symbol	Arguments	Explanation
Δt	$-$	time step lenght
γ_I	T	specific investment costs per unit of capacity addition
γ_L	T_L	learning costs
γ_F	T_L	floor costs
γ_{fix}	T	specific O&M costs - fixed part
γ_{var}	T	specific O&M costs - variable part, depending on amount of production
ι	e_p, g	cost per unit of fuel e_p with grade level g
η	T	efficiency of technology T.
ν	T	load factor of technology T
ν_r	T, g	resource availability factor
κ_0	T	share of initial main output production by technology T
ω	t_l, T	weight factor of addition to technology T's capacity prior to initial time
χ	s	capacity of stock of quantity s
ξ	e_{in}, e_{out}, T, e_s	own consumption coefficient
λ	e_p, e_s, T, y	emission of type y per energy flow in the energy transformation e_{in} into e_{out} using T
π_e	e_p, g	maximal production (according to energy type e_p) of primary energy from primary resource e_p of grade level g
π_T	g, T_{ren}	maximal production (according to technology T_{ren}) of secondary energy from non-exhaustible resource via T_{ren}, g
γ	e_p, g	cost per unit of fuel e_p with grade level g
ϵ	g, e_x	upper limit for cumulative extraction of an exhaustible ressource e_x of grade level g
D_{ex}	t, e_f	total demand of final energy of type e_f, computed from exogenously given initial value and annual growth rate
$Y_{CO_2,max}$	t	overall maximal amount of CO_2 emissions for each time step - defined externally
ρ	t	discount rate

Table A.4: Mappings

Symbol	Arguments	Explanation
$M_{e \to e}$	$e_{in} \times e_{out} \times T$	set of all technologies T transforming an energy type e_{in} into another e_{out}
$M_{p \to s}$	$e_p \times e_s \times T$	set of all technologies that transform e_p to e_s using T
$M_{s \to s'}$	$e_s \times e_{s'} \times T$	set of possible combinations of e_s, $e_{s'}$, T
$M_{s \to f}$	$e_s \times e_f \times T$	set of all technologies that transform e_s to e_f using T
M_{own}	$e_{in} \times e_{out} \times T \times e_{own}$	combinations of own consumption of e_{own} for the transformation from e_{in} to e_{out} via T
$M_{T \to Y}$	$e_{in} \times e_{out} \times T \times y$	set of all ways to produce emission type y from technology T which converts e_{in} into e_{out}
$M_{e_p,g}$	$e_p \times g$	set of all combinations of grade levels g and primary energy types e_p. Also applied as:
$M_{e_x,g}$	$e_x \times g$	set of all possible combinations of e_x and g
$M_{T \leftrightarrow g}$	$T \times g$	set of all possible characterizations of technologies T by grade levels g
$M_{T_s \leftrightarrow g}$	$T_s \times g$	set of all technologies producing secondary energy T_s that use ressources of grade level g
$M_{T_f \leftrightarrow g}$	$T \times g$	set of possible combinations of technologies T and grade levels g of secondary to final energy production
$M_{T \leftrightarrow t_l}$	$T_{vin} \times t_l$	set of possible combinations of vintage technologies T_{vin} and life time indices t_l
$M_{e_p \leftrightarrow g}$	$e_p \times g$	set of possible combinations of primary renewable energy types and grade levels

Table A.5: Abbreviations that are used for technologies

Abbreviation	Full name
pc	Pulverized coal power plant
pcc	Pulverized coal power plant with carbon capturing
ngcc	Natural gas combined circle power plant
ngccc	Natural gas combined circle power plant with carbon capturing
ngt	Natural gas turbine
wind	Wind turbine (onshore)
hydro	Large hydroelectricity
spv	Solar photovoltaic (central)
fnr	Fast nuclear reactor
tnr	Thermal nuclear reactor
fbr	*Fast breeder reactor (should be changed to fnr)*
lwr	*Light water reactor (should be changed to tnr)*
tnrfp	Thermal nuclear reactor, fuel production
tnrdd	Thermal nuclear reactor, direct disposal of spent fuel
tnrrep	Thermal nuclear reactor, reprocessing of spent fuel
fnrfp	Fast nuclear reactor, fuel production
fnrdd	Fast nuclear reactor, direct disposal of spent fuel
fnrrep	Fast nuclear reactor, reprocessing of spent fuel
pu2hlw	Conditioning of plutonium (for disposal as HLW)
hlwis2ts	HLW transportation and terminal storage
ilwis2ts	ILW transportation and terminal storage
llwis2ts	ILW transportation and terminal storage
ccscomp	Compression of captured CO_2
ccspipe	Transportation of captured CO_2
ccsinje	Injection of captured CO_2
ccsmoni	Monitoring of captured CO_2
tdel	Transportation and delivery of electricity

Table A.6: Abbreviations that are used for energy types and quantities

Abbreviation	Full name
pecoal	Coal (primary energy)
pegas	Gas (primary energy)
peur	Uranium (primary energy)
pehyd	Hydro energy (primary)
pewin	Wind energy (primary)
pesol	Solar energy (primary)
seel	Electricity (secondary energy)
feel	Electricity (final energy)
co2	CO_2 (emitted into atmosphere)
cco2	CO_2 (captured)
tnrfu	Thermal nuclear reactor fresh fuel
tnrpr	Thermal nuclear reactor spent fuel
fnrfu	Fast nuclear reactor fresh fuel
fnrpr	Fast nuclear reactor spent fuel
depur	Deriched uranium
recur	Recycled uranium (from reprocessing)
puis	Plutonium (interim storage, from reprocessing)
llwis	LLW (interim storage)
ilwis	ILW (interim storage)
hlwis	HLW (interim storage)
llwts	LLW (terminal storage)
ilwts	ILW (terminal storage)
hlwts	HLW (terminal storage)
tnrsfts	Thermal nuclear reactor spent fuel (terminal storage)
fnrsfts	Fast nuclear reactor spent fuel (terminal storage)

Table A.7: Abbreviations that are used for model equations

Abbreviation	Full name
goallp	Objective function
ccostfu	Calculation of fuel costs
ccostom	Calculation of O&M costs
ccostin	Calculation of investment costs
pebal	Balance equations for primary energy types
sebal	Balance equations for secondary energy types
eubal	Balance equations for final energy types
pe2setrans	Tranformation equations (primary to secondary energy)
se2eutrans	Tranformation equations (secondary to final energy)
se2setrans	Tranformation equations (secondary to secondary energy)
stockenty	Calculation of storage of quantities
stockconst	Constraint on storage capacities for quantities
ccap	Definition of annual capacities
capconstse	Capacity constraints for primary to secondary energy transformation
capconstse2se	Capacity constraints for secondary to secondary energy transformation
capconsteu	Capacity constraints for secondary to final energy transformation
capconstccs	Capacity constraints for transformation inside the CCS chain
llearn	Calculation of investment cost for learning technologies
capcummo	Calculation of cumulated capacities for learning technologies
fuelconst	Resource constraints for exhaustible energy sources
renconst	Potential constraints for renewable energy sources
emissions	Calculation of annual emissions
emiconst	Cap on annual emissions
ccsbal	Balance equations for the CCS chain
ccstrans	Transformation equations for the CCS chain
ccsconst	Constraint on CCS storage

Table A.8: Description of units. SI units and prefixes have been used wherever it was possible. This table only list the non-SI units.

Unit	Description
MtU	10^6 tons of uranium
MtHM	10^6 tons of heavy metal
ppm	parts per million
GtC	10^9 tons of carbon

Table A.9: SI prefixes.

Prefix	Equivalent
E	10^{18}
P	10^{15}
T	10^{12}
G	10^{9}
M	10^{6}
k	10^{3}

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Bibliography

[Archer und Jacobson 2005] Archer, Cristina L. ; Jacobson, Mark Z.: Evaluation of Global Wind Power. In: *Journal of Geophysical Research* 110 (2005)

[Bauer 2006] Bauer, Nico: *Personal discussion.* November 2006

[Bauer und Lueken 2006] Bauer, Nico ; Lueken, Michael: *genERIS – A Tool for Flexible Energy System Modeling. Documentation (version 0.2).* Milano and Potsdam: , 2006. – Unpublished Manuscript

[BMWA 2003] BMWA: Forschungs– und Entwicklungskonzept für emissionsarme fossil befeuerte Kraftwerke / Bundesministerium für Wirtschaft und Arbeit. URL http://www.fz-juelich.de/ptj/projekte/index.php?index=1325, 2003. – Bericht der COORETEC-Arbeitsgruppen

[BP 2006] BP: Statistical Review of World Energy / British Petroleum. 2006. – Forschungsbericht

[Chakravorty u. a. 2005] Chakravorty, Ujjayant ; Magné, Bertrand ; Moreaux, Michel: *Can Nuclear Power Save the Kyoto Protocol?* 2005. – URL http://www.bus.ucf.edu/uchakravorty/Working%20Papers/CMMNuclearSept06.pdf. – in review

[Chakravorty u. a. 2006] Chakravorty, Ujjayant ; Magné, Bertrand ; Moreaux, Michel: A Hotelling Model with a Ceiling on the Stock of Pollution. In: *Journal of Economic Dynamics and Control* 30 (2006), S. 2875–2904

[Dones u. a. 2005] Dones, Roberto ; Heck, Thomas ; Emmenegger, Mireille F. ; Jungbluth, Niels: Life Cycle Inventories for the Nuclear and Natural Gas Energy Systems, and Examples of Uncertainty Analysis. In: *International Journal of Life Cycle Assessment* 10 (2005), Nr. 1, S. 10–23

[DTI 2002] DTI: Managing the Nuclear Legacy / Department of Trade and Industry. Great Britain, 2002. – Forschungsbericht

[Edenhofer 2006] Edenhofer, Ottmar: *Personal discussion.* December 2006

[Edenhofer u. a. 2005] Edenhofer, Ottmar ; Bauer, Nico ; Kriegler, Elmar: The impact of technological change on climate protection and welfare: Insights from the model MIND. In: *Ecological Economics* 54 (2005), S. 277–292

[Edenhofer u. a. 2006] Edenhofer, Ottmar ; Lessmann, Kai ; Bauer, Nico: Mitigation Strategies and Costs of Climate Protection: The effects of ETC in the hybrid model MIND. In: *The Energy Journal Special Issue, Endogenous Technological Change and the Economics of Atmospheric Stabilization* (2006), S. 207–222

[EIA 2006] EIA: International Energy Outlook / Energy Information Administration. US Department of Energy, Washington, DC, 2006. – Forschungsbericht

[Enquete-Kommission des Bundestages 2002] Enquete-Kommission des Bundestages: *Nachhaltige Energieversorgung unter den Bedingungen der Globalisierung und der Liberalisierung (Endbericht).* Drucksache 14/9400. 2002

[Flechsig u. a. 2006] Flechsig, M. ; Böhm, U. ; Nocke, T. ; Rachimov, C.: *The Multi-Run Simulation Environment SimEnv.* 1.24. Potsdam Institute for Climate Impact Research (Veranst.), May 2006. – URL http://www.pik-potsdam.de/software/simenv/

[Frederick u. a. 2002] Frederick, Shane ; Loewenstein, George ; O'Donoghue, Ted: Time Discounting and Time Preference: A Critical Review. In: *Journal of Economic Literature* 40 (2002), S. 351–401

[Greenpeace 2006] Greenpeace: Reichweite der Uranvorräte der Welt / Greenpeace Deutschland e.V. URL http://www.greenpeace.de/themen/atomkraft/nachrichten/artikel/uran_fuer_atomkraftwerke_reicht_noch_maximal_65_jahre/, 2006. – Forschungsbericht

[Hoogwijk 2004] Hoogwijk, Monique M.: *On the Global and Regional Potential of Renewable Energy Resources*, Universiteit Utrecht, Dissertation, 2004

[IEA 2000] IEA: *Experience Curves for Energy Technology Policy.* International Energy Agency, 2000

[IEA 2005a] IEA: Key World Energy Statistics / International Energy Agency. 2005. – Forschungsbericht

[IEA 2005b] IEA: *Projected Costs of Generating Electricity.* International Energy Agency, 2005

[IEA 2006] IEA: MARKAL Homepage / Energy Technology Systems Analysis Programme (ETSAP). URL www.etsap.org/markal/main.html, 2006. – Forschungsbericht

[IEA/OECD 2003] IEA/OECD: *World Energy Investment Outlook.* Paris, France : International Energy Agency, 2003

[IPCC 2001a] IPCC: Climate Change 2001: Mitigation / International Panel on Climate Change. 2001. – Forschungsbericht

[IPCC 2001b] IPCC ; Nakicenovic, Nebojsa (Hrsg.) ; Swart, Rob (Hrsg.): *Special Report on Emissions Scenarios (SRES). Special Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom : Cambridge University Press, 2001

[IPCC 2005] IPCC ; Climate Change, Prepared by Working Group III of the Intergovernmental Panel on (Hrsg.): *Special Report on Carbon dioxide Capture and Storage.* Cambridge, United Kingdom and New York, NY, USA : Cambridge University Press, 2005

[Koelzer 2006] Koelzer, Winfried: *Glossary of Nuclear Terms.* Karlsruhe, Germany : Forschungszentrum Karlsruhe, 2006. – URL http://www.kernenergie.net [van Leeuwen und Smith 2005] Leeuwen, Jan Willem S. van ; Smith, Philip: *Nuclear Power: The Energy Balance*. 2005. – URL www.stormsmith.nl. – last opened: 01 / 2006.

[Matthes 2006] Matthes, Felix: *Mythos Atomkraft - ein Wegweiser*. Heinrich-Böll-Stiftung, 2006

[Mayer-Kuckuck 1994] Mayer-Kuckuck, Theo: *Kernphysik*. 6th. Stuttgart : Teubner Verlag, 1994

[MIT 2003] MIT: *The Future of Nuclear Power*. Massachusetts Institute of Technology, 2003

[NEA 1994] NEA: The Economics of the Nuclear Fuel Cycle / Nuclear Energy Agency. URL http://www.nea.fr/html/ndd/reports/efc/, 1994. – Forschungsbericht

[NEA 2002] NEA: Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles / Nuclear Energy Agency. 2002. – Forschungsbericht

[NEA 2003a] NEA: Nuclear Electricity Generation: What Are the External Costs? / Nuclear Energy Agency. 2003. – Forschungsbericht

[NEA 2003b] NEA: Uranium 2003: Resources, Production and Demand / Nuclear Energy Agency. 2003. – Forschungsbericht

[Nordhaus und Boyer 2000] Nordhaus ; Boyer: *Warming the world*. Cambridge University Press, 2000

[Quaschning 2006] Quaschning, Volker: *Regenerative Energien und Klimaschutz*. November 2006. – URL www.volker-quaschning.de

[Sano u. a. 2006] Sano, Fuminori ; Akimoto, Keigo ; Homma, Takashi ; Tomoda, Toshimasa: Analysis of technological portfolios for CO_2 Stabilization and effects of technological changes. In: *The Energy Journal Special Issue, Endogenous Technological Change and the Economics of Atmospheric Stabilization* (2006), S. 141–161

[Thomas 2006] Thomas, Steven: *The economics of nuclear power*. Kap. 5, S. 123–245. In: *Nuclear Power: Myth and Reality*, Heinrich-Böll-Stiftung, 2006. – URL www.boell.de/en/nav/275.html

[UNDP 2000] UNDP: World Energy Assessment: Energy and the challenge of Sustaineability / United Nations Development Programme. URL http://www.undp.org/energy/activities/wea/drafts-frame.html, 2000. – Forschungsbericht

[van der Zwaan und Rabl 2003] Zwaan, Bob van der ; Rabl, Ari: Prospects for PV: a learning curve analysis. In: *Solar Energy* 74 (2003), S. 19–31

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