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LONG-TERM PRICE UNCERTAINTIES OF FOSSIL PRIMARY FUELS AND IMPLICATIONS FOR THE ELECTRICITY INDUSTRY

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PREFACE

Die vorliegende Arbeit befasst sich mit der stochastischen Modellierung langfristiger Preisunsicherheiten bei fossilen Brennstoffen, insbesondere Kohle und Gas, und ihren Auswirkungen auf die Investitionsplanung von Energieversorgungsunternehmen. Sie entstand während meiner Zeit als externer Doktorand am Lehrstuhl für Energiewirtschaft (EWL) an der Universität Duisburg-Essen in den Jahren 2005 und 2006.

Mein besonderer Dank gilt meinem Doktorvater Prof. Dr. Christoph Weber für das mir entgegen gebrachte Vertrauen und die engagierte, konstruktive Betreuung meiner Arbeit. Bedanken möchte ich mich auch bei dem gesamten EWL-Team für die herzliche Aufnahme sowie die fortwährende fachliche und moralische Unterstützung. Besonders herausstellen möchte ich hierbei Oliver Woll, der mir in unzähligen Gesprächen wertvolle Anregungen für die Modellierungsarbeit gab. Prof. Dr. Erwin Amann danke ich für die Erstellung des Zweitgutachtens.

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Nicht zuletzt bedanke ich mich bei meiner Frau Alexandra für ihre Liebe, Geduld und Unterstützung. Besonders herzlicher Dank gebührt meinen Eltern, denen ich diese Arbeit widme. Ihre uneingeschränkte Förderung meiner Ausbildung und ihr liebevoller Beistand hat die Entstehung dieser Arbeit erst ermöglicht.

München, September 2009

Wolfgang Walther

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LIST OF ABBREVIATIONS

€	Euro
AAPG	American Association of Petroleum Geologists
AAU	Assigned Amount Unit
AFR	Africa (model region)
APP	Asia-Pacific Partnership on Clean Development and Climate
ARA	Amsterdam, Rotterdam, Antwerp
Art.	Article
ASIA	Asia (model region)
ASPO	Association for the Study of Peak Oil and Gas
BBC	British Broadcasting Corporation
bbl	barrel, 158.987 liters
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (German Federal Institute for Geoscience and Resources)
BMF	Bundesministerium der Finanzen (German Federal Ministry of Finance)
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (German Federal for the Environment, Nature Conservation and Nuclear Safety)
BMWI	Bundesministerium für Wirtschaft und Technologie (German Federal Ministry of Economics and Technology)
bn	Billion, 10^9
CAGR	Compound Annual Growth Rate
CAN	Climate Action Network
CCS	Carbon Capture and Sequestration
CDM	Clean Development Mechanism (Kyoto Protocol)
CER	Certified Emission Reduction
cf	Cubic Feet
cf.	confer
CIF	Cost, Insurance, Freight
CIEP	Clingendael International Energy Programme
CTL	Coal to Liquid (coal liquefaction)
d	day
DCF	Discounted Cash Flows
e.g.	for example [*Latin*: exempli gratia]
$_{el}$ [*subscript*]	electric
EEFSU	Eastern Europe and Former Soviet Union (model region)
EIA/ DOE	Energy Information Administration/ U.S. Department of Energy
EL	Electricity (model demand sector)
EnWG	Energiewirtschaftgesetz (German law regarding public energy supply)
ERU	Emission Reduction Unit

ET	Emission Trading (Kyoto Protocol mechanism)
EU	European Union
EURELECTRIC	Union of the Electricity Industry
et al.	and others [*Latin*: et alii/ alia]
f.	and the following page
ff.	and the following pages
f.o.b.	Free On Board
FR	Freight (model demand subsector off Transportation)
G8	Group of Eight: Canada, France, Germany, Italy, Japan, Russia, UK, U.S.A.
GAMS	General Algebraic Modeling Software
GDP	Gross Domestic Product
Gpkm	Giga Passenger Kilometer
Gtkm	Giga Ton Kilometer
GTL	Gas to Liquid (gas liquefaction)
GW	Giga Watt
ibid	at the same place [*Latin*: ibidem]
i.e.	that is [*Latin*: id est]
IAEE	International Association for Energy Economics
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis (Laxenburg, Austria)
IEPE	Institut d'Economie et de Politique de l'Energie, (until January 2003), Université de Grenoble, France
IER	Institute of Energy Economics and the Rational Use of Energy, University of Stuttgart, Germany
IN	Industry (model demand sector)
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation (Kyoto Protocol mechanism)
kW	Kilo Watt
LAM	Latin America (model region)
LEPII-EPE	Laboratoire d'Economie de la Production et de l'Intégration Internationale - département Energie et Politiques de l'Environnement (since January 2003), Université de Grenoble, France
LNG	Liquefied Natural Gas
LOTELMAS	Long-Term Electricity Market Simulation
LP	Linear Programming
MCP	Mixed Complementary Problem
MEA	Middle East (model region)
mill.	Million
MW	Mega Watt
MWh	Mega Watt-Hour, 1 MWh = 10^6 Wh

NAM	North America (model region)
NAP	National Allocation Plan
NEWAGE	National, European, World-wide Applied General Equilibrium Modeling System
NGO	Non-Governmental Organization
NLP	Nonlinear Programming
Nm^3	Norm Cubic Meter
NPV	Net Present Value
OECD	Organization for Economic Co-operation and Development
OGIP	Original Gas in Place
OOIP	Original Oil in Place
OLS	Ordinary Least Squares
OPEC	Organization of the Petroleum Exporting Countries
OTC	Over The Counter
p.	page
p.a.	per year [*Latin*: per annum]
PA	Passengers (model demand subsector of Transportation)
POLES	Prospective Outlook on Long-term Energy Systems (IEPE model)
RC	Residential & Commercial (model demand sector)
SAGE	System for the Analysis of Global Energy Markets (EIA/ DOE model)
SAUNER	Sustainability And the Use of Non-rEnewable Resources
t	Tons
$_{th}$ [*subscript*]	Thermal
tce	Ton of Coal Equivalent
toe	Ton of Oil Equivalent
TR	Transportation (model demand sector)
TWh	Tera Watt-Hour, 1 TWh = 10^6 MWh
UAE	United Arab Emirates
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
URR	Ultimate Recoverable Resources
U.S., U.S.A.	United States (of America)
US-$	United States Dollar
WBCSD	World Business Council for Sustainable Development
WDR	Westdeutscher Rundfunk (West German Broadcasting Service)
WEC	World Energy Council
WEM	World Energy Model (IEA model)
WETO	World Energy Technology Outlook (EU report)
WEU	Western Europe (model region)
Wh	Watt-hour

1 INTRODUCTION

Energy has become an essential resource for today's industrial societies. In particular, the availability of electricity is essential for the functioning of almost every sector of modern civilization, be it in industrial production, transportation, communication, housing, healthcare or any other sector conceivable. The effects of insufficiencies in the electricity supply system were shown dramatically through the blackouts in Europe and the U.S.A. in 2003.

Therefore, a timely and accurate planning of construction and deployment of power plant capacities is essential. Among all the decisions connected to the investment in a new power plant, the choice of fuel stands out. This decision will impact the profitability of a power plant until its very last day of operation, and, particularly for nuclear plants, even beyond. Unfortunately, future paths of fuel prices and CO_2 emissions costs are far from certain and thus investment decisions are taken under considerable uncertainty.

Fossil fuel prices are determined by multiple key drivers, e.g. not only of geological, economic, technological and environmental but also of geopolitical and financial nature. Each key driver bears an element of uncertainty concerning its future development, usually with the degree of uncertainty increasing over time. Any deterministic forecast of future developments of fossil fuel prices, especially for such long periods as required for power plant investments, is highly prone to error on multiple dimensions[1].

Often, decision makers try to incorporate uncertainties about future developments by defining different general scenarios with specific assumptions for each scenario. In general, a scenario can only consider (deterministic) data input defined for this specific setting. Any change in the current assumptions or the analysis of interdependencies with the assumptions from a different scenario[2] requires the setup of a new scenario which quickly leads to a large set of different scenarios and results, creating confusion rather than additional insights.

Especially, the underlying data and assumptions of a scenario may change over time, e.g. when updated information on producible resource volumes becomes available. This change of information can hardly be included in the standard de-

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[1] A comprehensive review of past oil price forecasts and an analysis of deviations between forecasted and actual prices can be found in Huntington (1994).

[2] As a simple example, consider the existence of a "CO_2 reduction scenario" and an "Increased demand" scenario in an energy supply and demand model, both to be compared with a baseline scenario. The joint consideration of both effects (reduced CO_2 emissions in combination with increasing demand) requires the setup of a fourth scenario.

terministic scenario technique. Instead, the definition of a new scenario is required once the new information about possible future developments becomes available.

Nevertheless, a sudden change or update of information is a common pattern in fossil fuel markets. Any framework or model related to the long-term development of fossil fuel prices should thus be capable of incorporating such data changes. This thesis aims at developing a model framework for fossil fuel price formation based on underlying fundamental data taking related uncertainties explicitly into account. In particular, the framework being developed should explicitly consider the occurrence of stochastic shocks in future periods to reflect the characteristics of fossil fuel markets. As a result, the framework should deliver projections of fossil fuels prices.

One possible application of such price series is to use them as input values for decision support systems for investments in new power plants[3]. By explicitly including uncertain fossil fuel prices into the investment decisions, it should be possible to increase the level of confidence and better substantiate such investment decisions.

In order to address the above research deficit and to develop a framework describing the impact of stochastic shocks on fossil fuel prices, the thesis will be divided into two major parts: a theoretical part in the chapters 2 to 6, and an empirical part in the chapters 7 and 8. Chapter 9 will summarize the thesis. An overview on the general structure is given in Fig. 1-1:

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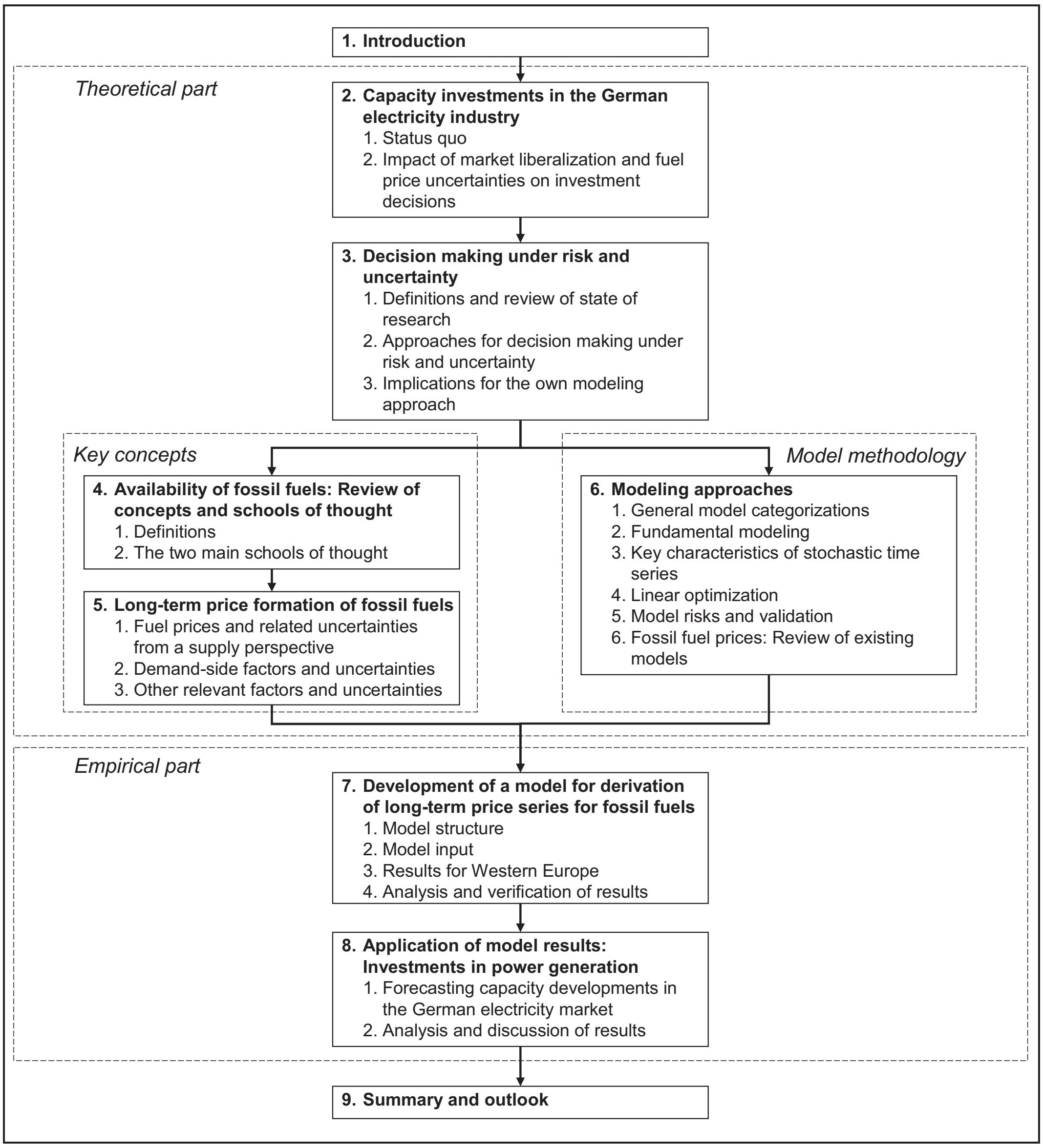
[3] E.g. as developed by Weber (2005b).



Source: Own representation

Fig. 1-1: Overview on thesis structure

The second chapter describes the status quo and thus the point of departure of the German electricity industry. In particular, the impact of market liberalization and uncertainties on investment decisions is considered. Chapter 3 defines the terms risk and uncertainty. Also, the chapter provides an overview on decision support techniques that can be applied in such circumstances. Specifically, the scenario technique which is frequently applied in the energy industry and the real options approach are discussed.

So far, point of departure and a generic theoretical framework for this thesis have been defined. For the development of an own model, a twofold approach will be followed here: Chapters 4 and 5 discuss the theoretical background of the model framework and content, i.e. fuel availability and key drivers of fossil fuel prices, whereas chapter 6 reviews the relevant modeling approaches. Chapter 7 and 8 form the empirical part of the thesis. In chapter 7, a model able to project fossil fuel prices, including the impact of stochastic shocks is developed. The price projections are then used in chapter 8 to derive investment strategies for the German electricity industry. Finally, chapter 9 provides a summary and an outlook on future research needs and opportunities.

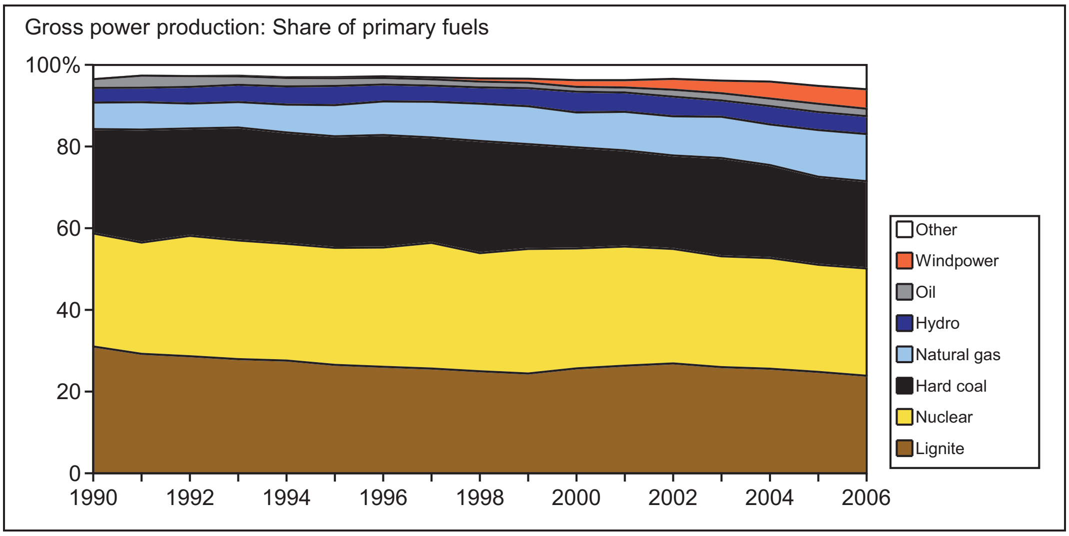
2 CAPACITY INVESTMENTS IN THE GERMAN ELECTRICITY INDUSTRY

Investments in generation capacity are currently an important issue for German (and European) electricity companies. This chapter briefly explains why new generation capacity is urgently needed at the moment and how uncertain fuel prices and CO_2 emission costs increase the risks related to these decisions. Using both the historical development and probable future trends, it is discussed in the first section why fossil fuels will continue to play such an important role in power generation and why this thesis is relevant for corporate planners in utility companies. In the second section, this chapter shows how market liberalization further complicates the situation.

Since the following discussion of the German electricity industry is primarily dedicated to the relevance of fossil fuel prices for investment decisions, it focuses very much on generation. Other steps of the value chain, like transmission and distribution, will not be considered in detail. Still, it should be kept in mind that the future portfolio of power plants is likely to impact investment decisions at least for the transmission grid, too. Few large-scale power plants fired by lignite, hard-coal or nuclear fuels require a different grid structure than a portfolio consisting of small distributed generation facilities (cf. e.g. Weber and Vogel 2005).

2.1 Status quo

Power generation in Germany is primarily based on three energy sources: lignite, nuclear fuels and hard coal. Fig. 2-1 shows the development of fuel shares in gross production since 1990.



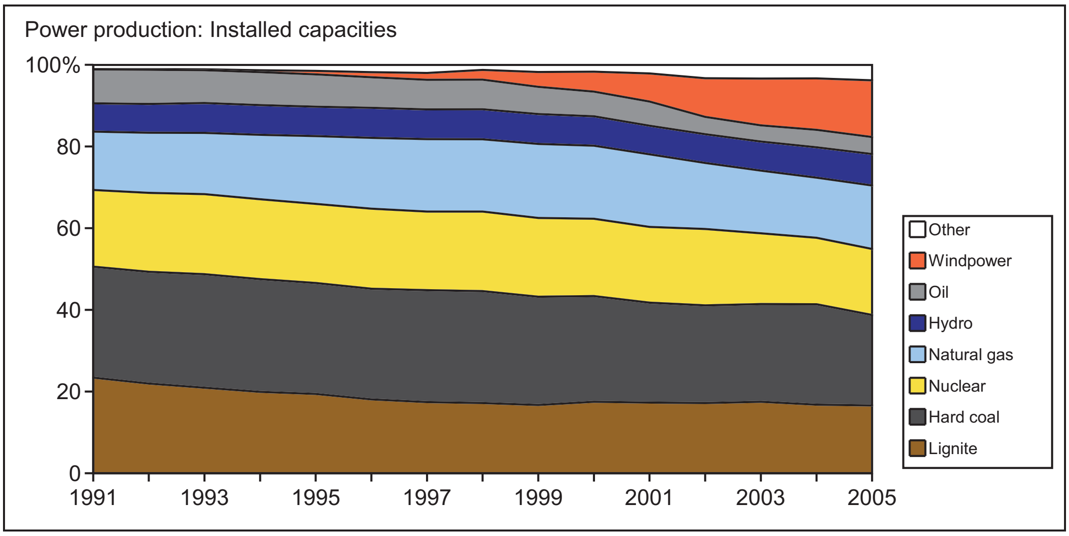
Source: Own representation based on BMWI (2007)

Fig. 2-1: Primary fuel shares in German gross power generation 1990 – 2006

In 2006, lignite is still holding the largest share with 24 percent although its portion has been decreasing from over 31 percent in 1990. This is partly due to the high specific CO_2 emissions of this technology and probably also to the change in the industrial landscape and electricity demand in former Eastern Germany resulting in a shut-down of lignite-fired plants there.

The second-largest share is currently being held by nuclear generation. The future development here is unclear: In 2000, a phase-out of nuclear generation had been agreed upon, creating an additional demand for generation capacity in the magnitude of 20 GW until 2020 (cf. e.g. Pfaffenberger and Hille 2004, p. 3.38f.). However, the revitalization of nuclear generation is currently being debated to reach the CO_2 emission targets.

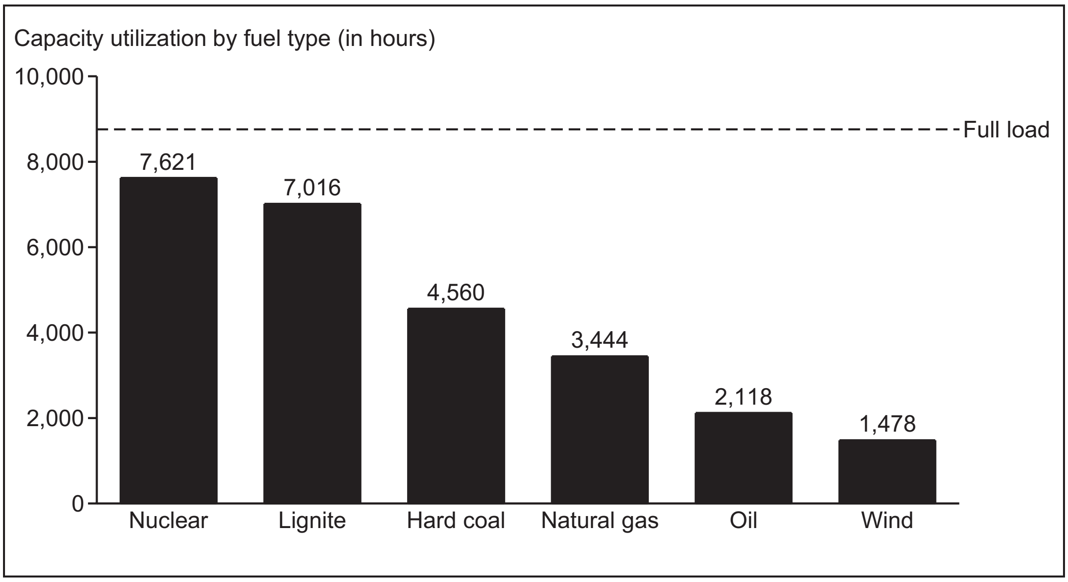
The development of installed capacities is similar, but not identical to the shares in gross production (cf. Fig. 2-2). Most obviously, the share of hard coal and natural gas is higher in installed capacity than in gross production due to the different load hours of power plant types (cf. Fig. 2-3). These technologies are primarily deployed in middle load and peak load generation, resulting in lower annual capacity utilization than for lignite and nuclear plants.



Source: Own representation based on BMWI (2007)

Fig. 2-2: Share of primary fuels in German installed capacity 1991 – 2005

Wind power capacities have experienced significant additions since the early 1990s (cf. e.g. Pfaffenberger and Hille 2004, p. 3.40f.). Largely, this has been driven by significant public subsidies to promote the usage of environmental-friendly renewable energy sources. Due to the wind-dependent and thus fluctuating production, wind power cannot be used to substitute the installed capacity of conventional thermal plants on a one-to-one basis. This is also reflected in the low capacity utilization of wind power plants as shown in Fig. 2-3. In addition, further onshore locations for wind power generation are limited since most good locations are being used already. Future installations are thus likely to be offshore facilities, requiring higher investments both in generation and in transmission networks. For the same reasons, a significant increase in hydro power generation is unlikely for Germany.



Source: Own representation based on BMWI (2007)

Fig. 2-3: Capacity utilization of German power plants in 2005

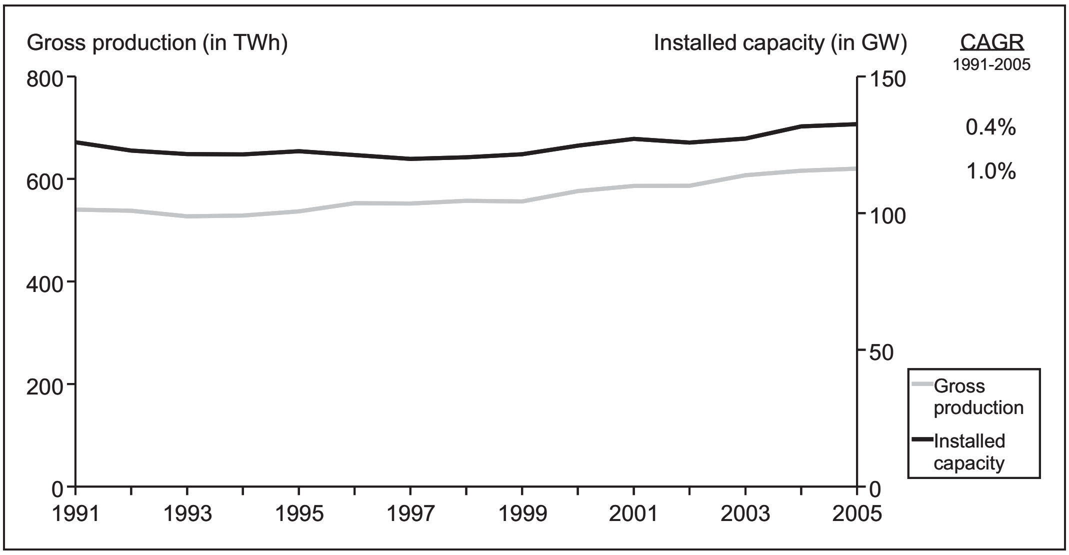
In summary, the mix of generation technologies in Germany is due to a wide range of key drivers (cf. e.g. Pfaffenberger 2002, Pfaffenberger and Hille 2004, Weber and Swider 2004, Pfaffenberger 2005 and Weber 2005a, 2005b):

- Fuel costs
- Diversification of fuel types to ensure the security of supply, especially after the oil crises in the 1970s (also cf. subsection 5.2.5)
- Environmental impacts, e.g. CO_2 emissions or ultimate waste disposal for nuclear fuels

- Technical specifications, e.g. ramp-up times, partial load efficiencies, minimum up- and down-times that are relevant for the possible modes of operation, i.e. the deployment for base or peak load generation[4].

Also for future investments, these four factors will continue to play an important role. The focus of this thesis is primarily on the theoretical discussion and model development related to the first point, i.e. fuel prices. Of course, this first point is significantly impacted by the second and third point, i.e. security of supply and environmental impact. The last topic, technical specifications, will be considered in the model applied in chapter 8 with regard to investment in generation capacities.

The levels of gross production and thus also of installed capacity have been rather constant over the last 15 years, as depicted in Fig. 2-4.



Source: Own representation based on BMWI (2007)
Note: CAGR = Compound Annual Growth Rate

Fig. 2-4: German gross production and installed capacity 1991 – 2005

Since many power plants are reaching the end of their technical lifetime[5] within the next years, substantial capacity investments are required to maintain the se-

---

[4] Lignite and nuclear plants are used for base load generation due to two reasons: First, their fuel costs are comparatively low, making the technologies ideal for 24/7 deployment. Second, they have long ramp-up times in the magnitude of several hours or even days, prohibiting the use in peak load generation. By contrast, gas-fired turbines have start-up times of a few minutes but high fuel costs. Therefore, they are used in peak load generation only, i.e. possibly only a few hours per year.

[5] Pfaffenberger and Hille (2004) assume a maximum lifespan of 40 to 45 years for power plants. They also allude to the fact that lifespan is not necessarily the limiting factor since revamping can significantly prolong the technical lifespan. However, old plants are not likely to reach the efficiency and thus the low operating costs of newly constructed plants.

curity of supply in Germany. Pfaffenberger and Hille (2004) calculated a total required investment of 40 to 50 GW until 2020. This includes the 20 GW needed from exiting nuclear-fueled generation.

Despite the efforts to promote renewable fuels in Germany and Europe, the major share of the replacement capacities is likely to be covered by fossil-fueled plants. Due to their fluctuating availability, most renewable energy sources cannot be used to provide 24/7 base load generation capacities. Significant electricity imports from other European countries are not an option either as the tight supply situation is the same all over Europe (cf. Weber and Swider 2004). Assuming that the nuclear phase-out will not be revised, fossil fuels remain the only large-scale technology available over the next decades until new technologies like thermonuclear fusion may become available. For strategic planners in utility companies, the key question is now to decide on the type of fossil fuels for new investments: "*Fuel prices affect the operation costs of the plants, and thus both prices and optimal capacities in a long-term equilibrium depend on observed or expected fuel prices*" (Weber 2005b, p. 242).

2.2 Impact of market liberalization and fuel price uncertainties on investment decisions

The liberalization of the German electricity industry started in 1998 when the law regulating public energy supply ("*Energiewirtschaftsgesetz*", EnWG) was amended[6]. The general objectives of the law include security of supply, cost effectiveness and environmental friendliness, sometimes also referred to as the *magic triangle* of energy policy. Later, also reasonable pricing and consumer-friendliness have been added to the objectives. Regarding power generation, cost effectiveness is to be realized by the breakup of regional monopolies, increased competition between utility companies and power plants, resulting in the reduction of monopoly rents. Also, an electricity exchange has been introduced, providing the possibility to trade spot and future contracts.

In a first phase, the liberalization led to a fierce competition on retail prices and saw both the entrance of new players and mergers of existing companies[7]. Since about 2002, the market has entered into a second phase in which market consolidation took place. In 2004, about 80 percent of the German generation ca-

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[6] It would exceed the scope of this thesis by far to discuss the detailed setup of utility deregulation and liberalization in Germany. Cf. e.g. Schulten (2004) for an overview and Schmitt (2007) for a discussion of future developments.

[7] In 2000, VIAG and VEBA merged to form E.ON. In 2002, RWE merged with VEW. The fusion of VEAG, BEWAG, HEW and LAUBAG led to the creation of Vattenfall Europe in 2002 (cf. Schulten 2004).

pacities were owned by one of the large four utility companies EnBW, E.ON, RWE and Vattenfall Europe (cf. Schulten 2004).

In summary, the liberalization created a number of strategic challenges for all utility companies. Customers are not assigned to a specific generation company any longer but can freely choose their supplier. Thus, utilities have to make efforts to gain and retain customers both on the wholesale and retail level. Their demand volume is no longer given within a certain range but fully depends on each company's ability to sell the production on the retail or wholesale markets, be it via long-term contracts, OTC contracts or at the energy exchange. Retail competition is complicated by the fact that electricity as a commodity offers little potential for differentiation. Also, due to the compulsory regional and economical separation of their transmission and distribution networks, known as *unbundling*, electric power companies are no longer allowed to cross-subsidize their operational divisions along the value chain. Power plants are thus increasingly required to operate as autonomous profit centers, valuating the produced electricity according to the mark-to-market principle, i.e. based on the corresponding spot prices (cf. e.g. Weber 2005b).

Regarding power plant investment decisions, the impacts are significant, too. Before the liberalization, utility planners could rely on quite stable demand patterns with minor stochastic fluctuations. Regarding prices, pre-liberalization utilities were able to pass on all their costs to their customers who were not allowed to switch suppliers. Consequently, also risks in primary fuel costs could be passed on to the customers. This provided little incentive for cost-optimal generation portfolios and deployment decisions. Now, liberalization has eliminated the guarantee of cost-covering prices in generation. Utility companies are confronted with uncertainties on multiple dimensions relevant for investment decisions: demand volume, attainable electricity prices and primary fuel costs, just to name the most important ones. In addition, there are several technical peculiarities connected to power generation that further complicate the investment decision. Leaving aside some pumped-storage power stations, there is no possibility for large-scale storage of electricity. Production and demand have to occur simultaneously. Reserve capacities are required to balance demand spikes.

The economic risk connected to power plant investments is particularly relevant due to the absolute size and lumpiness of investments. A hard coal-fired plant with an installed net capacity of 750 MW requires an investment of about €800M, a lignite-fired plant with 750 MW net capacity even around €1B. A 150 MW gas turbine can be built for around €35M but will cause significantly higher fuel costs (cf. Weber 2005b, p. 263). For a decision to invest in generation capacities in a liberalized market, the investor must be sure to realize his imputed interest rate over the entire lifespan of the plant, i.e. over a period of up to 40 years. Thus, expected electricity prices must be sufficiently high to cover the full investment costs. Also, marginal costs of the new plant must not exceed the marginal costs of existing plants. Otherwise the new plant cannot be operated profitably (cf. Pfaffenberger and Hille 2004, p. 9.6f.).

The importance of marginal costs is due to a specific pricing mechanism of the electricity wholesale market called *peak load pricing* (cf. e.g. Boiteux 1960, Pfaffenberger and Hille 2004, pp. 3.19 - 3.24, and Weber 2005b, pp. 32ff. and 229ff.). Peak load pricing refers to the fact that the wholesale electricity price is set by the production costs of the marginal producer. This means that the wholesale price equals the marginal costs of the last, i.e. most expensive, plant required to cover the current demand for electricity (cf. Weber 2005a). Key driver for the variable share of the marginal costs are primary fuels prices and other costs related to fuels, e.g. CO_2 emission or abatement costs. The unfavorable development of the price for a specific fossil fuel, e.g. natural gas, can mean that gas-fired plants are not able to regain their investment costs: "*The major market risk for any power plant investment in the longer run is that fuel prices (and/ or technology) develop in a way that a once-built power plant is not competitive any more. Thereby two cases have to be distinguished: one possibility is that the technology is no longer part of the efficiency frontier at all. Another is that the range of efficient operation hours (and consequently the optimally installed capacity) of the technology decreases. In both cases, the capacities already installed can still be operated, but they have to accept a reduced operation margin*" (Weber 2005b, pp. 245 - 246).

Also the volatility of fuel prices impacts the decision for or against a certain fuel technology. The higher the volatility of e.g. natural gas prices, the higher is the risk that capital-intensive technologies like hard coal-fired plants become economically inefficient (cf. Weber 2005b). If gas prices fall low enough, gas-fired plants can be operated profitably also for medium or even base load generation, squeezing out coal plants due to the lower investment costs of gas-fired plants. Therefore not only the average or median development of fuel prices must be considered but also their volatility.

As the above explanations have made clear, investment decisions related to generation capacities require not only the expected values of future fuel prices, but also a probability distribution of prices or at least a probable range of prices. The objective of this thesis is to project such a range for fossil fuel prices in chapter 7 and to apply it to investment decisions in power generation in chapter 8. However, prior to the development of a model, the underlying theoretical mechanisms for fuel price formation must be examined and formalized. Hence, chapter 3 reviews generic tools for decisions under uncertainty, and chapters 4 and 5 analyze the theoretical concepts and key drivers for fossil fuel availability and prices.

3 DECISION MAKING UNDER RISK AND UNCERTAINTY

Decisions under risk and uncertainty play an important role both for the analysis of future fuel price developments as well as for power plant investments. Thus, characteristics of and approaches for decision making under risk and uncertainty are discussed in this chapter. After introducing general definitions in the first section, selected approaches, both for decisions under risk and uncertainty, are discussed in the second section. The third section summarizes the most important findings for this thesis.

3.1 Definitions and review of state of research

The distinction between risk and uncertainty in economics goes back to Knight (1921): "*It will appear that a measurable uncertainty, or 'risk' proper, as we shall use the term, is so far different from an unmeasurable one that it is not in effect an uncertainty at all. We shall accordingly restrict the term 'uncertainty' to cases of the non-quantitive type*" (Knight 1921, p. I.I.26)[8].

Following this definition, *risk* denotes a state of imperfect knowledge in which all possible outcomes of a decision can be specified and assigned with a probability of occurrence[9]. Contrary to that, *uncertainty* characterizes situations in which either possible outcomes of a situation can be listed exhaustively but probabilities of occurrence cannot be assigned or in which possible outcomes cannot be completely enumerated at all[10]. Reasons for the inability to assign probabilities can be the lack of experience or missing historic data, for example. When a complete list of possible consequences cannot be compiled, it is often due to a fragmentary understanding of causalities.

The sharp distinction between risk and uncertainty is not kept up continuously in literature. In several publications (cf. e.g. Pindyck 1980, Dixit and Pindyck 1994, Birge and Louveaux 1997 as well as Bamberg and Coenenberg 2004), the term *uncertainties* is used even if the authors are discussing risks. Weber (2005b) therefore refers to uncertainties in a broader sense as a collective term for uncertainties in the narrow sense and risks.

Dasgupta and Heal (1979) distinguish exogenous and institutionally induced risks and uncertainties (cf. Dasgupta and Heal 1979, pp. 395ff.). The occurrence of

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[8] A similar definition can be found in Perridon and Steiner (1999), p. 99f.

[9] Bamberg and Coenenberg (2004) point at the fact that the probabilities can be either based on impartial, observable facts or on subjective assessments.

[10] Perman, Ma et al. (2003) refer to this second kind of uncertainty as "*radical uncertainty*" (cf. p. 445).

exogenous risks and uncertainties, e.g. due to missing information on the size of a mineral deposit, is independent of the market structures. Market or institutionally induced risks and uncertainties relate for example to decisions of other market participants, e.g. regarding investments, production volumes or speculation. The occurrence and magnitude of institutionally induced risks depends on the legitimacy of these activities: If speculation is prohibited, it cannot be a source of uncertainty. Fossil fuel prices and CO_2 emission costs are typically exogenous risks in power generation.

Birge and Louveaux (1997) add time as another relevant dimension. Following their argumentation, a long-term uncertainty, e.g. the development of a price series over five years, can be considered as the combination of several short-term uncertainties that occur frequently, for example on a weekly or monthly basis. In general, the degree of uncertainty is expected to increase with the temporal distance of the considered point in time.

Based on that, Weber (2005b) lists three primary sources of risks and uncertainties for companies active in energy-related industries: market, other external sources and internal sources (cf. Tab. 3-1).

Market	**Other external sources**	**Internal sources**
Time		
• Price • Quantity • Liquidity	• Counter-party • Political & regulatory • Financial	• Process & project • Personal • IT • Model

Source: Own representation based on Weber (2005b), p. 150ff., and Birge and Louveaux (1997)

Tab. 3-1: Sources of risks and uncertainties

Market-related risks and uncertainties can originate from unforeseen changes in prices or quantities as well as from the impact of poor market liquidity. Price risks and uncertainties comprise e.g. changes in spot, forward and future prices as well as in interest and exchange rates. Changes in quantity may arise from varying production capacities or developments on the demand side. Poor market liquidity further increases the significance of these sources of risk and uncertainty. In illiquid markets, already small changes in supply or demand volumes may lead to significant price changes, especially if the markets are characterized by limited capacities and confined extension possibilities.

Risks and uncertainties from other external sources may arise due to unexpected behavior of counter-parties, e.g. the failure of delivery due to bankruptcy. Political and regulatory decisions constitute another element of uncertainty, both in a national and international context. Financial risk refers to all monetary imponderables of a company.

Internal risks and uncertainties may be related to the design of new workflow processes or to the setup of new projects that do not achieve the expected results. Adding to that, a company's staff may induce further risks and uncertainties, as human actions can always be prone to error. Also the loss of expert knowledge due to quits is a threat falling into this category. Even criminal activities constitute a risk for the company's success. Due to the ever-growing importance of information technology and processing, deficiencies in the IT systems pose a major threat in nearly every aspect of business life. Companies are well advised to monitor all eventualities in this sector very carefully. Finally, also the models used to monitor, assess and control risks and uncertainties may be misspecified leading to wrong appraisals regarding risk exposure and counter measures.

For utilities, risks and uncertainties related to fossil fuel prices generally fall into the first of the three categories above, i.e. are primarily price and quantity risks. One could also argue that at least part of the risk is driven by political and regulatory key drivers, e.g. when considering CO_2 emission or abatement costs.

3.2 Approaches for decision making under risk and uncertainty

In this section, methodologies to support decisions under risk and uncertainty are presented: First, approaches for decisions under risk are introduced, in particular the Bernoulli or expected utility principle. In the second subsection, the classical decision rules for uncertain situations like the maximin and minimax rules are discussed. Third, selected practical approaches to deal with uncertainty are reviewed, i.e. the deterministic equivalent, the scenario technique and the real options approach.

3.2.1 Normative decision theory

An individual characteristic of each market participant is his or her willingness to accept risk in market transactions and investment decisions. This is expressed by the terms *risk aversion* and *risk preference*, a concept going back to Friedman and Savage (1948): Risk aversion is characterized by the preference for a certain but lower payoff (referred to as *certainty equivalent*), compared to a higher but uncertain payoff. The reverse case, i.e. the preference of a situation with a high but uncertain payoff over a lower certainty equivalent is then called risk preference or risk tolerance. The lack of any preference or aversion is referred to as *risk-neutral* behavior.

The explanation of risk aversion requires the employment of expected utility instead of expected monetary payoff because otherwise the choice of a lower payoff cannot be explained rationally. Bamberg and Coenenberg (2004) use the example of fire insurance for a better illustration: The calculation of the expected monetary value based on possible losses due to a fire, probability of occurrence and premium level would always lead to the conclusion that the optimal choice would be not to contract insurance. Still, many house owners choose to do so. Another example that the expected monetary value is not always the key driver of decisions can be found in the St. Petersburg paradoxon, as described by Bernoulli (1738)[11]. Based on his observations, Bernoulli introduces the *expected utility hypothesis*[12] (cf. Bamberg and Coenenberg 2004, pp. 81ff.). He postulates that each decision maker subjectively assesses the utility u from all possible monetary results X of a decision, using individual preferences or utility functions. As each individual tries to maximize his or her expected utility $E[u(X)]$ of a decision, action a is preferred over action b if

$$E[u(X_a)] \geq E[u(X_b)] \tag{3.1}$$

The utility preference of each individual is unknown and needs to be estimated. Ramsey (1931) proposes the usage of hypothetical decisions with two alternatives. In this setting, the probability of occurrence of the two alternatives is varied until the decision maker is indifferent between the two choices. Based on these results, risk preference, risk aversion or risk indifference of the specific individual can be determined. However, this seems to be a rather academic approach with no major relevance for real life situations due to constraints regarding time and representativeness.

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[11] The St. Petersburg paradox describes a gamble with an infinitely large expected gain. However, nobody would be willing to pay a large amount to participate.

[12] In German literature often referred to as *Bernoulli principle*, cf. Bamberg and Coenenberg (2004).

In literature, decision makers are often assumed to be risk-averse (cf. e.g. Markowitz 1970, p. 6, and Bamberg and Coenenberg 2004, p. 95), i.e. they prefer a smaller certainty equivalent over a larger, but uncertain, expected value. The deduction from the expected value leading to an indifferent assessment of the two choices is referred to as *risk premium* (cf. Bamberg and Coenenberg 2004, p. 96). The most basic approach to incorporate risk preference or aversion into investment decisions is to adjust the interest rate by a risk premium based on individual assessments and then calculate the *net present value* (NPV) or *discounted cash flow* (DCF) of an investment[13]. However, NPV/ DCF methods have some major deficiencies that can substantially distort the results, cf. subsection 3.2.2.3. For that reason, this approach will not be dealt with any further in the following sections.

Already prior to the introduction of the expected utility hypothesis by Bernoulli there have been approaches to formalize optimal decision making under risk. One methodology, known as the *Bayes' rule*[14] or *μ*-rule (cf. Perridon and Steiner 1999, p. 106, and Bamberg and Coenenberg 2004, p. 103), chooses the highest expected value of the alternatives. If objective probabilities or at least a probability range for each alternative cannot be determined, Perman, Ma et al. (2003) advocate to assume equal probabilities for each scenario, i.e. to apply the Laplace rule (cf. Bamberg and Coenenberg 2004, p. 133).

For investments under risk and uncertainty, decision rules need to make allowance for the lower degree of data availability, i.e. particularly the fact that probabilities of occurrence are ex ante unknown. Also, it should be kept in mind that a strategy which is optimal for each possible scenario cannot be found given the presence of future uncertainties: "*The concept of rational behavior is problematic in the face of uncertainty - there is no way of making decisions that can be unambiguously identified as doing the best for the decision maker in the relevant circumstances*" (Perman, Ma et al. 2003, p. 461). Thus, what was perceived as an optimal choice ex ante, may turn out to be wrong ex post.

Based on Perman, Ma et al. (2003) and Bamberg and Coenenberg (2004), there are four decision rules that can be applied to make an investment decision under uncertainty:

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[13] A brief discussion of this methodology can be found in Perridon and Steiner (1999), p. 101f., for example.

[14] Named after Thomas Bayes, a British mathematician of the 18th century.

- The *maximin rule*[15] chooses the strategy with the best payoff in the worst-case scenario. Perman, Ma et al. (2003) point out that this decision rule has a number of deficiencies. It is based on a negative general attitude, since only the worst cases are considered. Other information, e.g. regarding average or best payoffs of a strategy, is ignored. This means that a strategy with an only slightly better payoff in the worst case is preferred over a second strategy with a slightly lower worst payoff but significantly higher payoffs in all other scenarios.
- The *maximax rule* is similar to the maximin rule, but with the opposite prefix. It chooses the strategy with the highest payoff in the best case. Due to its similarity to the maximin rule, it is burdened with the same shortcomings.
- The third decision rule, the *Laplace rule*, adds all payoffs of one strategy over all possible scenarios. The strategy with the largest sum is considered as optimal choice. Implicitly, all scenarios are assigned the same probability of occurrence.
- The fourth decision rule, the *minimax regret rule*, chooses the strategy for which the maximum foregone payoff is lowest in case of the worst non-optimal scenario materializing.

While these decision rules are very easy to apply, they all suffer from a number of shortcomings. First, all four require the ability to calculate a deterministic NPV for each strategy-scenario combination. In multi-stage problems where random variables, e.g. prices or demand, are allowed to differ from stage to stage, this is hardly possible. Furthermore, especially the first two rules consider only a fraction of the information that is available. In general, it is questionable whether real world decision problems can be formally described as required for the above approaches.

3.2.2 Practical approaches for decision support

As the above discussion of decision rules under risk and uncertainties has shown, the approaches presented are not very suitable for real business decisions, either because they are too simplistic (like the maximin and maximax rules) or require information on risk preferences that is hardly available and difficult to measure (like the expected utility hypothesis). To compensate for that,

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[15] Also referred to as *Wald rule* after Abraham Wald, cf. e.g. Wald (1945).

three additional approaches are introduced below: deterministic equivalent, scenario technique and real options approach. Of these, especially the scenario technique is a methodology often applied in analyses of the fossil fuel markets.

3.2.2.1 Deterministic equivalent

The *deterministic equivalent* technique is described e.g. by Birge and Louveaux (1997). Typically, it is applied in optimization models to reflect stochastic behavior. It is based on the replacement of uncertain model parameters described by a probability distribution with their expected value. This means that instead of implementing the mathematical description of the underlying probability distribution in the model, the expected value e.g. of cash flows based on possible strategy-scenario combinations is applied. This significantly reduces model complexity and model computation time, but requires computing the appropriate expected values or deterministic equivalent[16].

3.2.2.2 Scenario technique

For the *scenario technique*, no single methodology exists. Various approaches have been developed simultaneously and continuously improved. However, there is a common understanding in literature (cf. e.g. Wack 1985a, Godet 2000 and Coates 2000), that the modern scenario technique goes back to the work of Herman Kahn, an U.S. futurologist dealing with possible developments in the Cold War after 1945.

Godet (2000) defines a scenario as a "*set formed by the description of a future situation and the course of events that enables one to progress from the original situation to the future situation*" (p. 11). Also, he distinguishes two types of scenarios: *Explanatory* scenarios are of purely descriptive character. They are built on the observation of past and current developments and sketch the likely future, primarily by extrapolating the observed developments. *Anticipatory* or *normative* scenarios go one step further. They are based on substantially different visions of the future, leading to an either desired or feared environment. While the former scenario type can be considered as a business-as-usual case that requires only gradual changes in strategy, the latter type of scenarios may require significant changes in corporate strategy and organizational setup.

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[16] For any multi-period stochastic linear problem with a finite number of scenarios, probabilistic constraints can be replaced with their deterministic equivalents. Cf. Birge and Louveaux (1997), pp. 85 - 100, for a thorough discussion of mathematical requirements for calculations of appropriate expected values.

Godet (2000) also emphasizes that scenarios must not be confused with the set of strategic options available to a decision maker or company. The realization of scenarios is almost completely detached from the actions taken by the decision maker while the strategic options describe his possibilities to (re-)act. In Godet's view, the degree or extent of uncertainty is expressed by the number of scenarios required to appropriately describe the range of future developments. However, a limitation in the number of scenarios presented to decision makers to a maximum of four to six is recommended (cf. e.g. Wack 1985a, Coates 2000 and Godet 2000).

Coates (2000) identifies five major steps for developing scenarios: First, the relevant environment, or, as he called it, the "*universe of concern*" (p. 117) of the decision making entity, needs to be identified and defined. Next, the key variables that are most likely to be the drivers of future developments must be defined. In a third step, about two of these key variables are grouped to themes, one for each scenario. After that, the scenarios are created by considering the key variables per theme and assessing their likely results which can be either of quantitative or qualitative nature. At this point, the scenarios primarily describe the states of the environment the company may be exposed to in future (explanatory or descriptive scenarios). In the fifth and final step, the descriptive scenarios need to be transformed to normative scenarios by including recommended or required strategic actions. As Godet (2000) notes, this entire approach can require a substantial effort in time and resources, up to several man-years.

The application of scenarios is particularly popular in the energy industry. One of the first companies to apply this technique on a broad scale was Royal Dutch Shell (cf. Wack 1985a, 1985b). Other prominent examples include Elf and the EDF Group (cf. Godet 2000).

Royal Dutch Shell has been using scenario planning since the early 1970s to forecast possible developments in the crude oil market. As this topic is closely related to the focus of this thesis, the approach and its results are examined a bit more in detail. The first usage of scenarios was due to the insight that traditional forecasting, i.e. primarily the extrapolation of current trends, is on the one hand often correct because "*the world does not always change*" (Wack 1985a, p. 73). On the other hand, extrapolation must fail when major changes or disruptions occur in the industry. Thus, Shell developed a set of descriptive "*first-generation scenarios*" (Wack 1985a, p. 77) in 1971 to 1973. They already included the most relevant uncertainties in the crude oil market at that time. However, they were primarily aimed at improving the understanding of market forces and not at recommending specific strategic actions for Shell. Still, already before the first oil crisis, an analysis of these scenarios led to the insight that the oil industry was to experience significant changes over the next years: An increasingly tight supply situation would change world oil markets from buyers' to sellers' markets. "*We did not know how soon it would occur, how high the price increase would be, and how the various players would react. But we knew it would happen*" (Wack 1985a, p. 85).

Wack (1985b) also points out that the definition of (first-generation) scenarios is not sufficient to effectively influence decision makers. He realizes that divergent alternatives often lead to confusion among decision makers who rather "*yearn for some kind of 'definiteness' when dealing with the uncertainty*" (Wack 1985b, p. 2). Thus, he recommends the development of *decision* or *second-generation scenarios*, similar to the normative scenarios introduced above. They must be aimed at changing the mindset and perception of the decision makers to make them aware of possible developments and strategic options they have not considered before. With regard to the number of scenarios for that purpose, Wack (1985b) considers three scenarios as optimal: The first one serves as reference or business-as-usual case without major surprises or interruptions. The two other scenarios reveal the developments based on the most critical uncertainties. When developing the three scenarios, the objective should not be to perfectly describe the future situation but rather to display the most relevant key drivers for the future development, their interrelations and the uncertainties attached to them. Wack (1985b) also advises not to construct the three scenarios along one parameter or dimension (e.g. low, average and high oil price) because decision makers will then be tempted to regard the middle scenario as the most likely development, preventing them from developing new perspectives beyond their current horizon.

By using multiple scenarios, scenario planning allows the consideration of developments that are uncertain at the point in time when the scenarios are defined. However, it does not provide the possibility to incorporate potential information updates that occur at some later point in time. In other words, each scenario pertains to one deterministic development without the option to incorporate changes in the set of information later on. This shortcoming is addressed by the real options approach discussed in the next section.

3.2.2.3 Real options approach

The real options approach, described notably by Dixit and Pindyck (1994) and Trigeorgis (1996), constitutes an important contribution to the inclusion of uncertainties into the decision making process. Following Dixit and Pindyck, the traditional assessment of investment decisions, i.e. calculating the NPV of all cash flows and investing if the project has a positive NPV, has two major flaws when applied to decisions under uncertainty. First, it does not take into account the irreversibility of investment costs. When a company- or industry-specific investment has been made, all or large part of the investment costs are sunk costs and cannot be recovered. One example for company-specific sunk costs are marketing cost. For industry-specific investments that should be considered as sunk costs, the authors quote production facilities as an example. Given the case of overcapacities in the industry, the investing company will hardly be able to recover the construction costs when selling the facility to a competitor. This peculiarity is not reflected appropriately in the common NPV calculation. The second point left out is the incorporation of the option to postpone investments and wait for better information. Since this option to postpone has many similarities to financial options (cf. e.g. Hull 2006), it is called *real option*. The decision maker has the choice of either exercising his option in the current period and making the investment or to abandon the option for the current period and decide again in the next period. Once the option has been exercised, this choice is not available any longer due to the irreversibility of the investment. The opportunity cost of lost flexibility should therefore be included when assessing the profitability of investment projects. Conventional NPV calculation does not provide this possibility. Here, an investment is always a *now or never* decision. "*Opportunity cost of investing can be large, and investment rules that ignore it can be grossly in error*" (Dixit and Pindyck 1994, p. 6). The higher the degree of uncertainty regarding future developments, e.g. trends in prices or demand, or the higher the investment costs, the more the option value increases.

The classical tool to incorporate risk or uncertainty into investment decisions is adjusting the interest rate. However, this does not reflect the value of the postponement option as both the value of investing and the value of waiting are affected simultaneously. Instead, the option value of waiting should be expressed as the difference of the values for an investment in the current period and for an investment in the next period when additional information, e.g. on prices, is available.

The real option approach is able to eliminate many of the shortcomings identified for the classic decision rules above. Still, it requires the ability to quantify all decision variables and probabilities. In addition, significant hardware resources might be required to compute medium- to large-scale problems.

Real options represent a sophisticated approach to deal with investment decisions under risk. In particular, it allows quantifying the value of postponing an investment decision. It can be argued whether or not it fully reflects reality because it assumes perfect knowledge of all probabilities, and is therefore probably one major reason why this technique is not very frequently applied for actual business decisions.

3.3 Implications for the own modeling approach

In this chapter, the terms *risk* and *uncertainty* have been distinguished, based on the data availability regarding possible outcomes and their probabilities. This section also shows that fossil fuel markets are subject to a large variety of short- and long-term risks and uncertainties, both from internal and external sources. The influence of these risks and uncertainties on the decision of a given decision maker depends on the individual risk preference or aversion. Decisions in fossil fuel markets have primarily to deal with uncertainties as not all possible outcomes can be listed nor can all related possibilities be defined.

The second section discusses decision rules for investment decisions under risk and uncertainty. These approaches are primarily *normative* models, i.e. they define the steps required to make the best possible decision. However, as fossil fuel markets comprise many different players with various objectives and incentives, this does not fully reflect reality. Thus, a *descriptive* model, i.e. a model describing how decisions in reality are actually made, seems more appropriate for the problem at hand. In particular, descriptive results of fossil fuel prices will allow drawing conclusions about the behavior of relevant decision makers in an aggregated view. Thus, individual decision makers will be able to include this information into their decision.

An advanced numerical methodology to model and support decisions under uncertainty requires a substantial amount of data input and a good understanding of the interrelations between the various key drivers. Only with this information available, will it be possible to appropriately model the fossil fuel markets and their immanent uncertainties. For the problem at hand, i.e. the long-term development of fossil fuel prices, primarily data on fuel availability and other cost drivers is needed. Thus, the next two chapters will look into the qualitative aspects of these factors, discussing the large number of key drivers. In addition, not only the value or specification of each single factor may change over time but also the impact of each key driver as it may be either amplified or weakened by other factors.

4 AVAILABILITY OF FOSSIL FUELS: REVIEW OF CONCEPTS AND SCHOOLS OF THOUGHT

This chapter aims at giving an overview on the past and current discussions regarding the remaining volumes of fossil fuels available for production and consumption. An assessment of available fuel reserves and resources is important because availability is expected to have a significant impact on prices. Availability can have a direct impact on costs and prices when the perception or existence of scarcity (i.e. a reduced availability) results in levying a royalty or scarcity rent, payable to the resource owners. Also indirectly, a reduced availability is likely to raise fuel prices by creating higher expenditures for exploration, development and production. As this chapter will show, the availability of natural resources in general and fossil fuels in particular has been the subject of many discussions between scientists, economists and politicians for many decades. In his discussion of the British coal production, Jevons (1866) concludes "*that we cannot long maintain our present rate of increase of consumption; that we can never advance to the higher amounts of consumption supposed*" (Jevons 1866, p. XII.29). Still, he regards this more as a problem of rising costs than as a depletion problem.

Likewise, the fear for depleted oil deposits is nearly as old as commercial oil production itself (cf. Simon 1996, pp. 165ff., and McCabe 1998, p. 2111). A.J. Hazlett writes in the Oil Trade Journal in 1918: "*At regularly recurring intervals in the quarter of a century that I have been following the ins and outs of the oil business there has always arisen the bugaboo of an approaching oil famine, with plenty of individuals ready to prove that the commercial supply of crude oil would become exhausted within a given time — usually only by a few years distant*" (quoted in Fanning 1950, p. 322).

The first section of this chapter is dedicated to the definition of terms that are being used throughout this thesis[17]. Although some of the terms are quite frequently used – also in non-scientific settings – it turns out that there are important nuances in the meaning of some terms that can make a significant difference in this context. Therefore a clarification seems necessary. The second section reviews selected theories and frameworks that have been developed to forecast the availability of fossil fuels. Although most of the methodologies have primarily been applied to crude oil, they can be transferred to other fossil fuels without major adaptation.

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[17] Further definitions of technical terms (with focus on oil and gas) can be found in Schlumberger (2007).

Clearly it is not the intent of this thesis to make one's own predictions about the extent of remaining deposits of fuel fossil – but for the further analysis of fuel price formation an assessment needs to be made whether any fuel under consideration will experience significant depletion effects during the considered period.

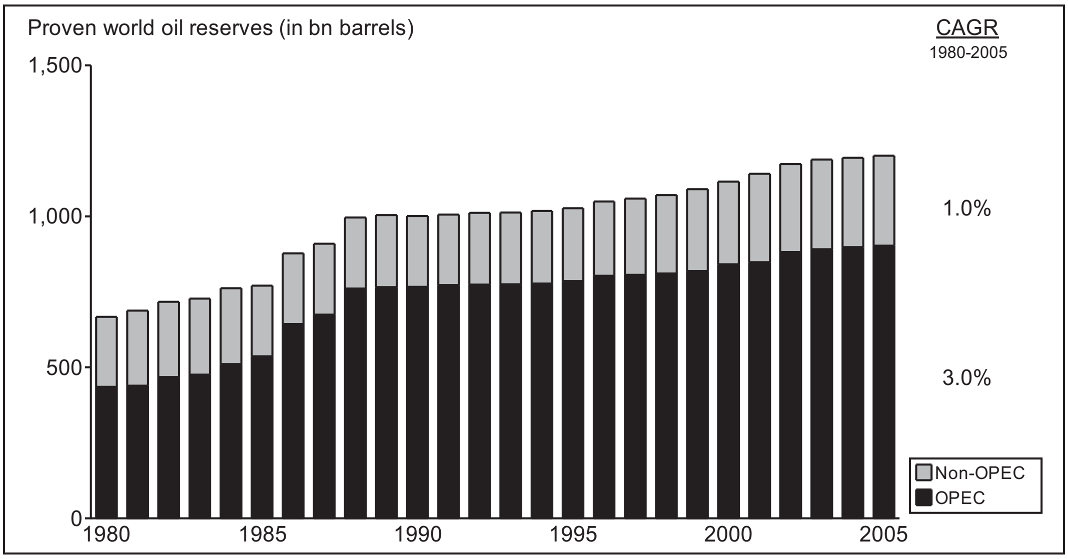
4.1 Definitions

4.1.1 Reserves

Following the definition of the American Association of Petroleum Geologists (AAPG, cf. Kumar 2001), *reserves* of fossil fuels are identified deposits of hydrocarbons that can be mined profitably given the current geological knowledge, technological progress and economic conditions. The AAPG distinguishes three levels of certainty regarding size and quality of the accumulation: "*proven*", "*proven plus profitable*" and "*proven plus profitable plus possible*" (Kumar 2001, p. 3). Ivanhoe (1995) proposes a similar definition: Reserves are the deposits categorized as producible by conservative-minded engineers.

Campbell and Laherrère (1998) as well as Simmons (2005a) advise caution regarding the use of company-issued reserve numbers: Especially in the oil and gas industry, reserves are considered as one of the key benchmarks for assessing the value of a company. This creates an incentive to assess the reserves in the upper range when communicating to investors, and in the lower range, when dealing with the fiscal authorities.

The total reserve of a certain fuel is a dynamic variable subject to permanent change. New discoveries or upward reassessments of existing reserve numbers add to the size of the reserve, production and downward reassessments however reduce the size of the reserve. If in a given year additions exceed production, the reserve number will rise compared to the previous year. BP (2006) report an average annual growth for proven world oil reserves of 2.4 percent from 1980 until 2005 (cf. Fig. 4-1). Also the market price of a specific fuel is relevant for the reserve number since the price defines the amount that can be produced economically (cf. Simmons 2005a).



Source: Own representation based on BP (2006)
Note: CAGR = Compound Annual Growth Rate

Fig. 4-1: Proven oil reserves 1980 – 2005

Due to the permanent changes, reserve numbers are not suitable for calculations of the remaining years of production (cf. McCabe 1998, p. 2113f.). Reserve numbers provide only a snapshot of the situation in one specific year and should not be taken as the maximum that is available for future production. “*Even in the later stages of resource use, there is really no ‘fixed’ reserve base (in an economically meaningful sense) to be exhausted over time. Given the economic incentives, reserves can be maintained or increased through further exploration - even though the physical returns to exploration decrease as ‘depletion’ ensues. It therefore makes more sense to think of resources like oil and uranium as being ‘nonrenewable’, rather than ‘exhaustible’*” (Pindyck 1978, p. 843).

4.1.2 Resources

The existence of the fuel deposits characterized as *resources* is by far less certain than for reserves[18]. The AAPG defines resources as “*potential, undiscovered, estimated hydrocarbons* […] *based on our current state of geological knowledge and existing technology*” (Kumar 2001, p. 3). There are three levels to indicate the quality of the estimate: “*low estimate*”, “*best estimate*” and “*high estimate*”. The categorization is based on the quality and quantity of available data

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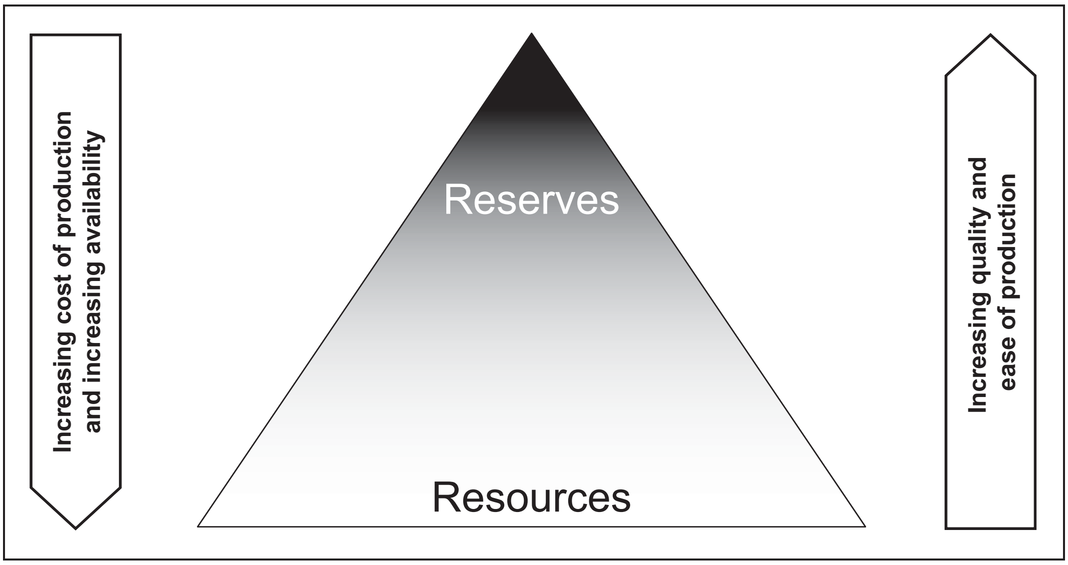
[18] A literature research shows that many authors do not give an unambiguous answer whether reserves are part of the resources or not (cf. e.g. Ströbele 1987, Hensing, Pfaffenberger et al. 1998 as well as Kumar 2001). However, according to the classification of the United Nations, they are defined as “*part of the total resources*” (cf. UNFC 2004, p. 3).

for each particular deposit. In order to increase the quality of an estimate, exploration activities are required. Ivanhoe (1995) characterizes resources as optimistic assessments of geologists.

Even if the existence and size of a resource deposit becomes more certain, it will only be re-classified as part of the reserve if its production becomes economically viable. Once a deposit and its geological specifications have been identified, the economic viability of production depends on both the cost of production, primarily driven by geological specifications and technological progress, and the market price, driven by the balance of demand and supply (cf. Ströbele 1987).

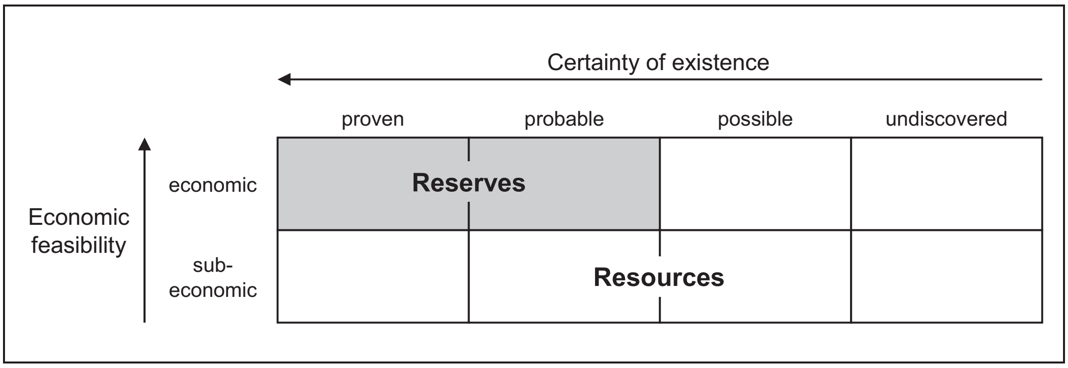
A popular concept to illustrate the relationship between reserves and resources is the resource pyramid (cf. McCabe 1998, p. 2116, and Bradley 1999, p. 63) as shown in Fig. 4-2. The top of the pyramid is composed of the high quality, easy producible reserves that are available only in limited quantities. Moving from top to bottom in the pyramid, both quality of the deposits and ease of production decrease. Consequently, costs of production increase. On the bottom of the pyramid, resources can be found that most likely will never be produced due to their poor cost-benefit ratio. A typical example often used in literature is gold dissolved in seawater: The total amount is huge but the concentration is so low that production will never become economically viable.



Source: Own representation based on Bradley (1999), p. 63

Fig. 4-2: Resource pyramid

A second framework to illustrate the interrelations between reserves and resources is the so-called McKelvey diagram (cf. Fig. 4-3). Based on the two dimensions *certainty of existence* and *economic feasibility*, reserves and resources are distinguished.



Source: Own representation based on Ströbele (1987), p. 58,
Hensing, Pfaffenberger et al. (1998), p. 28 and UNFC (2004)

Fig. 4-3: McKelvey diagram

A really unambiguous distinction of reserves vs. resources does not exist. A significant part of the assessment has to rely on experience and expectations of the future price and cost development. Therefore, the exact sizes of reserves and resources cannot clearly be defined and are subject to constant change. As demonstrated above, due to the requirement of economic viability for reserves, technological advances and market price have a continual impact on the boundary between reserves and resources. The general trend for oil is perceived to be shifting the boundary further down in the resource pyramid (cf. McCabe 1998). This can be best seen by the increasing economic relevance of so-called unconventional or continuous oil deposits like tar sands and shale oil. For hard coal on the other hand, the trend is often in the other direction. The decline of the West European coal industry can be considered as a good example, rendering reserves once considered as economically viable into resources.

4.1.3 Original Oil in Place (OOIP) and Original Gas in Place (OGIP)

Closely related to the concept of reserves and resources are the terms *Original Oil in Place* (OOIP) and *Original Gas in Place* (OGIP), cf. e.g. McCarthy and Torres (2004), p. 156, and Simmons (2005a), p. 266. The concept is applicable for coal as well, but is hardly found in literature.

The terms describe the total amount of hydrocarbons that a deposit contains before production begins. This number is usually far above the amount that finally can be produced. For Saudi Arabian oilfields, Simmons (2005a) estimates that 20 to 45 percent of the OOIP are producible.

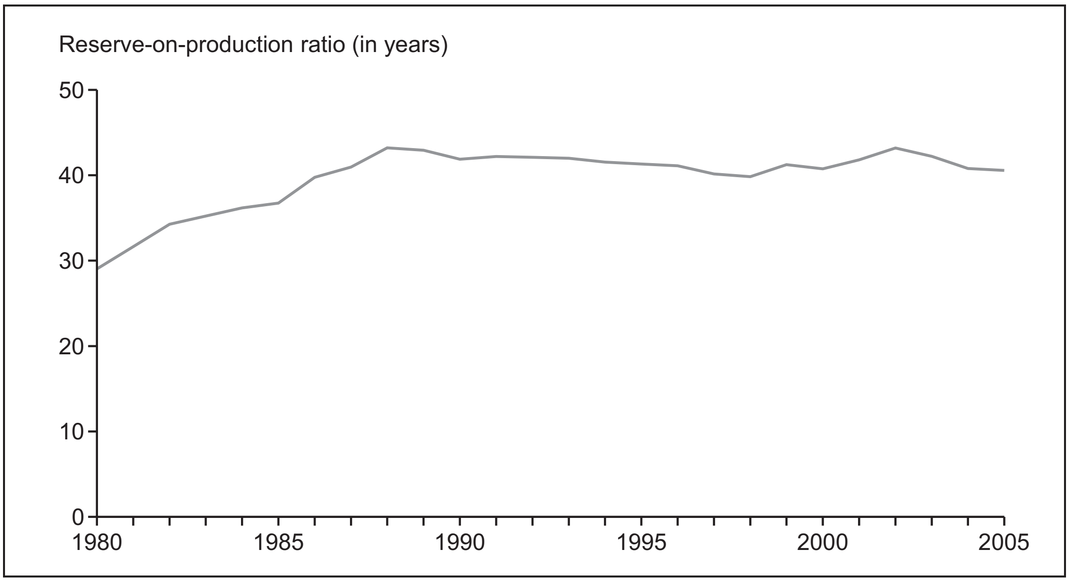
4.1.4 Ultimate Recoverable Resources (URR)

Ultimate Recoverable Resources refer to the total quantity of a fossil fuel that can possibly be produced based on the estimated OOIP or OGIP, respectively. Ultimate Recoverable Resources consist of the cumulative production (i.e. the amount of fuel produced over time) plus identified reserves plus resources that are likely to come into production at some point in the future.

As discussed above, both reserves and resources are variables that can change quite significantly over time, which raises the question as to whether URR figures are changing over time, too. The basic idea of the concept is that the URR are static but experience shows that URR figures are changing, too, e.g. due to new technologies: "*Estimates of URR are static, based on historical data, without giving sufficient attention to technological improvements raising the recovery factor of fields and decreasing the costs of depletion*" (Bollen, Manders et al. 2004, p. 49). Lynch (2002) assumes a growth of URR figures in the magnitude of 2 percent per year.

4.1.5 Reserve-to-production ratio

The *static reserve-to-production ratio* is calculated – as indicated by the name – by dividing the current proven reserve volumes by the current annual production. The result equals the range of fuel availability in years, assuming constant reserve and production volumes. In accordance with the above definition of reserves, this may at best be a relevant measure for a single mineral deposit, but should be treated extremely carefully in an environment with changing reserve figures and annual production volumes. Fig. 4-4 shows that the static global reserve-to-production ratio for crude oil has been relatively constant or even increasing over the last 25 years, despite the fact that annual oil production in 2005 was about 29 percent higher than in 1980, based on BP (2006) data.



Source: Own representation based on BP (2006)

Fig. 4-4: Global reserve-to-production ratio for crude oil

The attempt to include future developments of these factors leads to the calculation of the *dynamic reserve-to-production ratio*, which incorporates growth rates both for reserves and production. However, since these growth rates are very uncertain in the long term, the information content of dynamic reserve-to-production ratios is questionable.

4.1.6 Supply and demand

Kumar (2001) points out that, with regard to fossil fuels, an exact understanding of the terms *supply* and *demand* is mandatory: Based on the concept of reserves and resources, the available supply quantity refers only to the production capacity of existing wells or mines. Any deposits labeled as resources cannot be included into the calculation of supply quantities in the presence or near-term future since a conversion into producible reserves requires exploration and development, i.e. time and investment.

Consequently, demand is defined as the quantity of fossil fuels that is used to satisfy the current need for energy. Demand can be satisfied either with fuels coming right out of production or from stock piles. From the inclusion of stockholding into the balance of supply and demand it follows that supply (i.e. production) and demand (i.e. consumption) need not be identical for one specific period in time.

While the above definitions are commonly accepted in the scientific community, their respective values, notably the URR figures for fossil fuels, are contested. There are two major parties holding very differing views with regard to fuel availability or scarcity. Their views and arguments are presented in the next section below.

4.2 The two main schools of thoughts

In his review of the debate concerning the availability of fossil fuel, McCabe (1998) divides the participants of the discussion into two segments: the Neo-Malthusians and the Cornucopians.

The name of the *Neo-Malthusians* is derived from the name of Thomas R. Malthus, a British economist who published an essay on the interaction of resource availability (i.e. food) and population growth (cf. Malthus 1798). In his work, Malthus postulates that population is growing faster than the resource base required to fulfill human needs[19]. He argues that the size of the population should be kept at a level where resource consumption is still sustainable. Neo-Malthusians in terms of McCabe's definition are concerned about current levels of energy production and consumption. They fear the near depletion of nonrenewable fossil fuels and advocate the change to an energy supply based on renewable fuels. Also, overpopulation and continuous decrease of environmental quality are considered as major and pressing problems by adherers of the Neo-Malthusian school of thought. While this view is widely shared in the public, McCabe argues that the Neo-Malthusian approach is primarily driven by a misinterpretation of the concept of resources and reserves as static data, as discussed in the previous section of this chapter.

The opposite point of view is held by the *Cornucopians*, who deny the danger of an energy scarcity in the near- or mid-term future and distrust the significance of reserve and resource numbers. They argue that, in the past, human inventive talent and creativity always have found ways to circumvent impending shortages of natural resources by enhancing the productivity of existing technologies, e.g. in food production, or by introducing new technologies with different resource requirements. Julian L. Simon, one of the main proponents of the Cornucopian school of thought, uses the example of energy supply in England to support his

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[19] One of the best-known contemporary scientists on human overpopulation and resulting supply shortages is Prof. Paul R. Ehrlich, Stanford University. Since his focus is not on minerals and fossil fuels in particular, his work will not be further discussed here. For further references and a list of publications cf. http://www.stanford.edu/group/CCB/Staff/Ehrlich.html (accessed May, 12, 2007).

theory (cf. Simon 1991b, p. 257, and Myers and Simon 1994, p. 197): Due to deforestation from massive use of wood for heating and industrial purposes, England faced a major energy shortage in the 17th century. The discovery of coal as a major supply of energy made these fears irrelevant. When in the 19th century worries about an impending coal depletion came up, technological development made oil a more efficient and more convenient fuel than coal ever was. In the end, Great Britain has never had to experience serious energy shortages despite the long history of fears concerning this matter.

Lynch (1999) argues that "*no mineral has ever 'run out', nor has any mineral ever experienced long-term rising price trends*" (p. 119). Typically, Cornucopians expect the fuel price to display a mean-reverting pattern around a constant or even declining long-term average price. In their view, short-term fluctuations in price are primarily due to political and speculative influences but not to long-term fundamental trends in fuel availability.

Subsequently, some of the main representatives of both schools of thought are presented and their work is discussed. Based on these viewpoints, implications for the modeling of fuel depletion in this thesis are drawn.

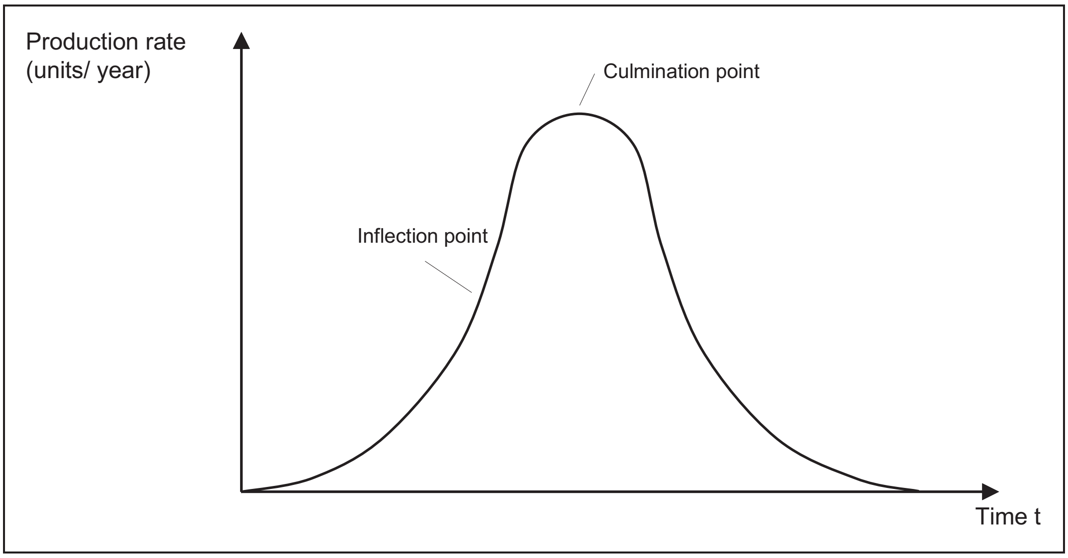
4.2.1 Neo-Malthusians: Industry experts fearing depletion

4.2.1.1 Hubbert's production curve

The analysis of Hubbert (1956) is one of the key cornerstones of the Neo-Malthusian viewpoint. Until today, there is hardly any publication discussing the availability of fossil fuels that does not refer to Hubbert in one way or the other, either building on his methodology or discarding it.

Hubbert bases his work on several assumptions. He argues that due to the protracted conversion process of organic material to fossil fuels, the available resource base is limited and will not be renewed or grow significantly during the exploitation phase. In a graph that shows cumulative production over time, the area under the production curve equals the total producible amount of a resource, the Ultimately Recoverable Resources (URR). Hubbert observes a tendency of production rates of a specific fuel deposit to grow exponentially. He concludes that, no matter how large the initial deposit of a fuel is, such a growth can be sustained only for a short period of time until the deposit is depleted.

The analysis of cumulative production of coal, crude oil and natural gas over aperiod of time in Texas, in the U.S. and on a global level leads him to the conclusion that each production curve shows the same characteristics: The typical production curve, showing production rate over time, starts slowly and then starts to increase steeper until it reaches an inflection point. Beyond the inflection point the slope decreases gradually and a culmination point is reached. Beyond the culmination point the curve decreases laterally reversed so that the total production curve is bell-shaped (cf. Fig. 4-5).



Source: Own representation based on Bradley (1999), p. 63

Fig. 4-5: Idealized Hubbert curve of production

Assuming that the production rate at the beginning and the end of production is zero and that the available resource base is limited to static URR figures, Hubbert is able to derive production curves. He uses historical data on production rates to derive the slope of the curve and predicts the culmination of U.S. oil production in the lower 48 states before the year 1970. For the production of natural gas, Hubbert comes to a similar conclusion: U.S. production is expected to culminate approximately 1970. While for oil production his prediction proved to be about right, U.S. production of natural gas in 1998 more than doubled the predicted peak.

For Hubbert's advocates, his theorem is still valid and could not be rejected so far. Ivanhoe (1995) states that *"the only truly valid scientific projection of future oil production yet made was that by M. King Hubbert in 1956*" (p. 86). Ivanhoe applies the Hubbert methodology to current data of global oil production and concludes that peak production is to be reached around the year 2000. He assumes stabilization at that production level for about 50 years until the inevitable decline later on. He infers that "*decline time for the global industry is not that far away*"

(Ivanhoe 1995, p. 87). Campbell and Laherrère (1998) praise the accuracy of Hubbert's predictions and use his methodology to analyze world oil production. They expect a peak in production during the first decade of the 21st century, i.e. in accordance with Ivanhoe's results.

Also a lot of criticism on Hubbert's approach is expressed by various authors. McCabe (1998), who objects the applicability of Hubbert's approach in general, discards the conclusion that the methodology is accurate only because the predictions for oil are accurate. He points out that, despite a very similar appearance of the curves, the bell-shaped Hubbert curve is not related to a classic Gaussian distribution curve. The resemblance with the Gaussian distribution curve is a point often stressed as indicator of the scientific integrity of Hubbert's hypothesis. McCabe emphasizes that in a Gaussian distribution, the individual data points are statistically independent from each other, and time is not a relevant dimension. Contrary to that, in a Hubbert curve, each data point depends on the data point from the previous time period.

Deming (2000) also calls attention to the point that Hubbert does not use any mathematical equations to derive the bell-shaped production curve but basically draws them by hand based on his assumptions about exponential increase and decline of production rates. This casts a shadow on the assessment by Ivanhoe (1995) who regards the Hubbert curve as "*the only truly valid scientific projection*" (p. 86): A unique, reproducible Hubbert curve does not exist. In another review of Hubbert's methodology, Laherrère (2000) develops an equation-based framework to reproduce a Hubbert curve. After discussing various types of curves[20] that resemble the Hubbert curve, he concludes that an adaptation of the derivative of the logistic curve comes closest to the original curve.

Regardless of any other remarks about the methodology as such, both Deming (2000) and McCabe (1998) agree that a correct assessment of the Ultimate Recoverable Resources (URR) is critical to derive any meaningful results from Hubbert's curve. Since the URR figures are subject to constant changes, the practical applicability of this approach on a global level remains questionable. Deming (2000) notes that "*Hubbert apparently never considered that the size of the finite resource base might be a moving target, thus invalidating his entire approach*" (p. 11).

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[20] E.g. Gauss curve, sine wave and parabola.

Another point of criticism raised by McCabe (1998) is that Hubbert's approach completely neglects political and economic factors. The implicit assumption for the Hubbert curve is that reserves go into production as soon as they are confirmed. This is generally true for crude oil reserves but much less for reserves of coal and natural gas. Here, the exploitation of reserves often is postponed several decades for political or economical reasons. In this case, the assumption of a bell-shaped curve is no longer justified.

Laherrère (2000) agrees that data series including economic and political factors are not appropriate for the computation of a Hubbert curve. Furthermore, he admits that the existing data must at least have reached the inflection point of the production curve to come to fair results. To achieve even good results, the underlying data must have exceeded the culmination point. In this case, the additional information generated by a Hubbert-style analysis, i.e. its predictive power, seems limited.

In addition, Smith (2007) shows that the fact that a peak in production occurs is not sufficient to come to any meaningful conclusions about remaining production volumes. In a simple model, he demonstrates that by changing assumptions about elasticity of the demand and economic growth, the peak of an oil production curve over time can be shifted from the middle of the time horizon to either the beginning or the end of the production. Resource stock, cost per unit, initial demand and cost of the backstop technology remain the same in all three cases. Smith (2007) concludes that "*even under the simplest (easiest) of assumptions: 1. The Peak doesn't signal whether remaining resources are plentiful or scarce. 2. The Peak doesn't signal whether current prices are high or low. 3. The Peak doesn't signal whether future output will fall precipitously or gradually (or fall at all)*" (p. 19). Supporting this view, Holland (2008) presents four oil production models in which production can peak at any point in time, unrelated to the remaining resource volume. He concludes "*first, that production peaks are not a reliable indicator of the amount oil remaining, and second, that prices are a better indicator of impending resource scarcity than production*" (p. 76).

In summary it can be said that, despite its initial intuitive plausibility, Hubbert's peak theory does not contribute significantly to answering the question of fuel availability: "*Hubbert-style analysis, invoked by many Neo-Malthusians as a demonstration of how quickly energy resources may be depleted, does not hold up to scrutiny of its basic assumptions*" (McCabe 1998, p. 2132).

4.2.1.2 The Report to the Club of Rome

One of the most famous publications regarding the forecast of energy supply is the book "*Limits to Growth*" by Meadows, Meadows et al. (1972) that became known as the "*Report to the Club of Rome*". The authors argue that a continuation of the 1972 growth trends of world population, industrialization, pollution, food production and depletion of natural resources would not be sustainable. Their calculations, based on the reserves known in 1972 and on an extrapolation of the exponential demand growth observed so far, show that the world's crude oil and natural gas deposits will be depleted in the 1990's, whereas global coal deposits will be exhausted around 2080.

Only one year after the publication, the oil shock of 1973 brought an end to an era in which public wisdom assumed that oil would be available at very low costs and without any significant limitations. The predictions in the report to the Club of Rome suddenly experienced high public attention and raised discussions about the sustainability of resource exhaustion (cf. McCabe 1998, p. 2111, and Simmons 2005a, pp. 52 - 55). However, from the ex-post perspective the analysis concerning the range of coverage for oil proved to be clearly wrong as oil and gas did not experience depletion in the 1990s. McCabe (1998) attributes this to a static misinterpretation of the concept of reserves and resources as explained in section 4.1.

4.2.1.3 The Association for the Study of Peak Oil and Gas (ASPO)

The Association for the Study of Peak Oil and Gas (ASPO) is a group of scientists focusing on the validation and further development of Hubbert's peak oil theory[21] (cf. e.g. ASPO Deutschland 2007, ASPO USA 2007 and peakoil.net 2007). It was founded by the British geologist Colin J. Campbell in 2000 (cf. e.g. Campbell 1997a, 1997b, as well as Campbell and Laherrère 1998). ASPO defines its mission as "*defining and evaluating the world's endowment of oil and gas; modeling depletion, taking due account of demand, economics, technology and politics; raising awareness of the serious consequences for Mankind*" (ASPO 2007, also cf. Campbell and Sivertsson 2003).

Since 2002, ASPO has been holding annual "*International Workshops On Oil & Gas Depletion*". In their publications, ASPO representatives are skeptical about officially published figures regarding crude oil reserves and expect the peaking of oil production around 2010 (cf. Drews 2006). Kjell Aleklett, the President of ASPO

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[21] Laherrère (2003) also uses the Hubbert curve to model population developments in various countries until 2050 or even 2100.

in 2007, also states that he still believes the *Report to the Club of Rome* by Meadows, Meadows et al. (1972) to be accurate: "*The Club of Rome published their Limits to Growth report a year before the OPEC states turned off the oil tap. We know now what followed: the world economy went into recession and demand for oil fell dramatically while at the same time there was a change in people's perceptions. Had this not happened the Club of Rome predictions would have been right*" (quoted in Drews 2006).

In detail, ASPO builds its projections of oil and gas production curves on three pieces of information (cf. e.g. Campbell and Laherrère 1998): cumulative production to date, estimated reserve figures and size of conventional deposits yet to be discovered. These figures then add up to the URR. For cumulative production, being an ex post value, there are relatively reliable data sources without major deviations. So far, this is identical to the approach described in section 4.1. When it comes to estimated reserves, the assessment gets much more complicated.

First of all, sizes of mineral deposits need to be estimated, creating an inherent degree of uncertainty. Deposit sizes can only be specified in combination with a probability. According to Campbell and Laherrère (1998), the definition of reserves is not consistent across different regions, i.e. there is no agreement on the probability required for the existence of a deposit to qualify as part of the reserves. Another point of criticism raised by Campbell and Laherrère is that the development of reserves is often estimated by extrapolating past data into the future, thus neglecting the increasing depletion of existing deposits and the declining discovery rate of new deposits.

Second, ASPO distrusts the announcements of both private and public sources, claiming that both companies and governments active in oil production have significant incentives to overstate reserve figures. Companies are assumed to publicize reserve figures in a way that best suits their corporate strategy and stock price[22]. OPEC countries have the incentive to exaggerate their reserves in order to maximize their production quotas. Also non-OPEC countries are assumed to report higher reserve figures although their motivation is not properly explained in Campbell's and the ASPO publications (cf. e.g. Campbell 1997b, p. 82).

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[22] Cf. Campbell and Laherrère (1998), p. 79: "*Exaggerated estimates can, for instance, raise the price of an oil company's stock.*" Contrary to this view, Campbell (1997b) states that "*major companies tend to understate initial reserves for a variety of motives*" and that only "*smaller companies sometimes overstate with their eye on the stock market*" (p. 72). Obviously, there is an inconsistency in Campbell's line of arguments: If only smaller companies with relatively small reserves overstate their reserve figures, whereas big oil companies understate their figures, the overall industry reserves figures should be rather adjusted upwards instead of downwards as proposed by ASPO.

ASPO representatives come to significantly lower estimates of reserve figures than those reported in the *Oil and Gas Journal* and *World Oil*, which are generally the reference sources for public reserve figures. For example, the estimates of Campbell and Laherrère (1998) for 1996 crude oil reserves are only 83 percent of the *O&G Journal* assessment and only 73 percent of the *World Oil* assessment from the same year.

Regarding the methodology of estimating future deposits, both Campbell and Laherrère (1998) as well as Campbell and Sivertsson (2003) criticize the established approach of allocating upside revisions of existing deposits to the year of the actual revision. Instead, revisions should be backdated to the year of the initial discovery of the deposit: "*The failure to backdate reserve revisions gives the false impression of perpetual growth*" (Campbell and Sivertsson 2003, p. 4). Applying this methodology, they conclude that global oil discoveries peaked in the early 1960s.

Following the ASPO reasoning, this reveals clearly that for crude oil, the vast majority of deposits have been discovered and that an imminent shortage is inevitable: "*It is important to realize that spending more money on oil exploration will not change this situation. After the price of crude hit all-time highs in the early 1980s, explorers developed new technology for finding and recovering oil, and they scoured the world for new fields. They found few: the discovery rate continued its decline uninterrupted. There is only so much crude oil in the world, and the industry has found about 90 percent of it*" (Campbell and Laherrère 1998, p. 81).

Campbell's view is supported by Matthew R. Simmons, Chairman of Simmons & Company International, an investment bank focusing on the energy industry (cf. Simmons & Company International 2007). He has held presentations at various ASPO conferences (cf. Simmons 2004, 2005b and 2006) and published a book on the situation of the Saudi Arabian oil industry called "*Twilight in the Desert*" (cf. Simmons 2005a). Based on his review of some 250 Technical Papers from the Society of Petroleum Engineers discussing technical issues of Saudi Arabian oil production, he especially highlights the fact that the vast majority of oil stems from less than ten super giant and giant oilfields, each discovered 40 to 60 years ago.

He claims that these fields have reached or are going to reach maturity soon, i.e. that their past and current production rates cannot be kept up perpetually. Adding to this, discoveries of new deposits equivalent in size have been very limited over the last 35 years and also non-conventional oil deposits will not be able to offset declining supply from the super giant oil fields.

Possible objections against the ASPO viewpoint are almost identical to those against the Hubbert curve: First, the assessment is based on a static understanding of the Ultimate Recoverable Resources and second, the fact of reaching a peak in production does not necessarily provide insights into future development of production.

4.2.2 Cornucopians: The economists' view

4.2.2.1 Morris A. Adelman: Volume flows instead of fixed stocks

Adelman is a strict advocator of the Cornucopian school of thought. Opposing the approaches described above, he strongly dismisses the concept of resource scarcity: "*There is no such thing as 'limited resources.' The amount of any mineral in the earth is an irrelevant non-binding constraint*" (Adelman 1993, p. 4) and "*A popular question has always been: 'When will the oil give out?' A one-word answer – never – is correct, but does not take us far*" (Adelman 2002, p. 172).

In his discussion of world oil supply, Adelman (1993) suggests considering flows of reserve-additions instead of fixed reserve numbers. To illustrate his point, he cites proven oil reserve figures for both the United States and the Persian Gulf Region as examples. In 1930, proven crude oil reserves in the United States were estimated to account for 13 billion bbl, and 20 billion bbl in 1990. Furthermore, 124 billion bbl had been produced in these 60 years, more than nine times of the 1930 estimate. Also in the Persian Gulf, proven and possible reserves were estimated at 21 billion bbl in 1944. Thirty-one years later, only the fields considered in 1944 had produced 42 billion bbl and were estimated to hold additional 75 billion bbl. Discoveries of other oil fields in the region are not even included in this number (cf. Adelman 1993, pp. 10 and 12).

Adelman also advises against interpreting the fixed stock as the share of natural resources that are economically viable to produce as this share depends on future costs and prices. Taking the stock ex ante as a given, would thus mean taking future costs and prices as constants as well: "*One cannot estimate costs and prices by starting with their result. The 'economic portion' is a forecast, an implicit unverifiable prediction of how much inventory will be worth creating and using*" (Adelman 1993, p. 4).

In Adelman's framework, the flow of reserve-additions is determined by the replacement costs of a consumed unit of fossil fuel. The long-term development of replacement costs is determined by two opposite trends. On the one hand, one would assume replacement costs to rise over time due to decreasing sizes of newly-found deposits and decreasing quality of the produced resource. This is derived from the theses that large deposits are likely to be found first and that better resource grades are produced first. On the other hand, there is increasing knowledge and improving technology of fuel extraction, driving down replacement costs. Following Adelman (1993), the observed low oil prices, especially prior to 1990, are due to the fact that "*so far, the human race has won big. This need not continue. We need to look at each mineral separately, and monitor the amount and cost of the flow of reserve additions*" (Adelman 1993, p. 5). As it is the case for hard coal resources in Western Europe, it is far more likely that the demand for a given resource will cease due to cheaper alternatives than the actual depletion of that resource: "*A mineral industry runs out of customers before it can run out of mineral*"[23] (Adelman 2002, p. 172).

The negation of long-term scarcity of natural resources – at least based on past observations – also leads Adelman to a different perspective on price formation of fossil fuels. As this chapter primarily deals with fuel availability, Adelman's theory on price formation processes will be reviewed in section 5.1 which looks into price formation.

Adelman's concept is vehemently opposed especially by representatives from the ASPO who are primarily engineers and geologists. Several publications from Campbell contain side blows against "*some economists* […] *who should know better*", referring in particular to "*Adelman and* [Peter] *Odell, the high priests of this heresy* [of unlimited resources]" (Campbell 1997b, pp. 71 and 80): "*On the one side, stand the Natural Scientists, with practical experience of the oil business, who have been trained to observe Nature and apply its immutable physical laws; while on the other, lie the Classical Economists, who deny that resource constraints can arise in an open market*" (Campbell and Sivertsson 2003, pp. 1f.). However, besides these rather non-scientific comments, hardly any objective discussion or even refutation of the Adelman's arguments can be found from the ASPO school of thought. Campbell (1997b) dedicates a full chapter (cf. Campbell 1997b, pp. 125 - 135: "*Economists Never Get It Right*") to the theory of "unlim-

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[23] This view is supported by a famous quote from the former Saudi-Arabian oil minister Sheik Ahmed Zaki Yamani in the 1970's: "*The Stone Age didn't end for lack of stone, and the oil age will end long before the world runs out of oil*", quoted in Maass (2005).

ited" natural resources but only revolves around the statement that economists are not able to understand the concept of limited resources and base their forecasts only on extrapolation of past data.

4.2.2.2 Julian L. Simon: Founding father of the Cornucopians

Julian L. Simon is perceived as one of the founding fathers of the Cornucopian school of thought. Other than Adelman, who dedicates much of his work specifically to the availability of crude oil, Simon also attends to natural resources in general, population trends and other fields of economics[24]. Still, his and Adelman's view on resource availability are very similar.

A cornerstone of Simon's work is his conviction that the average person creates more welfare than he or she consumes. "*Human beings create more than they use, on average. It had to be so, or we would be an extinct species.* […] *It applies to all metals, all fuels, all foods, and all other measures of human welfare, and it applies in all countries, and at all times*" (Myers and Simon 1994, p. 197). In Simon's eyes, this also justifies the higher consumption of resources per capita in the U.S.A. compared to less developed regions because "*the average American also creates a great deal more of 'natural' resource X than does the average African or Asian - on average, by the same or greater proportion as the resource is used by Americans compared with Asians and Africans*" (Simon 1996, p. 43). Based on this argumentation and the fact that prices of natural resources compared to wages have been falling over decades or even centuries (cf. e.g. Barnett and Morse 1963 as well as Simon 1996), Simon states that the usage of natural resources increases availability instead of reducing it.

Simon (1991a) also challenges the usefulness of reserve numbers to forecast availability in general. He compares known reserves to the stock of groceries of a household. In order to keep inventories as low as possible, households will only stock groceries required for the next couple of days or weeks plus provisions for unforeseen supply shortages. Following Simon, the amount of groceries in the households does not provide any insights on the amount of food available in the supermarkets. The same logic is then applicable for reserves of crude oil and other minerals: "*The amount of food in our cupboards tells little or nothing about the scarcity of food in our communities, because it does not as a rule reveal how much food is available in the retail stores. Similarly, the oil in the 'cupboard' - the*

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[24] Cf. Simon (2007) for a list of publications.

quantity of known reserves - tells us nothing about the quantities of oil that can be obtained in the long run at various costs" (Simon 1991a, p. 260).

Looking at past reserve numbers and their development, Simon seems to be right. However, one could argue that his analogy is based on circular reasoning as this behavioral pattern of households might be only observable where households are confident that they can stock up on supplies any time because food is always available in sufficient quantity. In societies where the availability of food or other supplies is not taken for granted at all times, e.g. in Third World countries or centrally planned economies, households are much more likely to stock up on supplies simply because they are available at the moment and not because they are required in the short term. Regarding natural resources, this would mean that the negligence of reserves as indicator of availability is due to the fact that we have never experienced really significant supply shortages so far.

Simon's answer to that is simple. He argues that history does not provide any evidence for, as he calls it, "*negative discontinuities*", i.e. the sudden unavailability of energy and natural resources. Instead, he rather expects "*positive discontinuities*", referring to the introduction of new energy sources we probably cannot even think of at the moment (Simon 1996, pp. 169f.).

4.2.2.3 Peter R. Odell: Ongoing dominance of fossil fuels

Similar to Adelman, the focus of Peter Odell's work has been on the availability of oil and natural gas (cf. e.g. Odell and Rosing 1980). He is convinced that the energy demand in the entire 21st century will still largely be satisfied by fossil fuels (cf. Odell 2004). Still, he expects the relevance of oil for the global energy supply to be reduced, with natural gas becoming the most important single fuel, especially after 2050. "*Gas will undoubtedly be the fuel of the 21st century (as coal was of the 19th century and oil of the 20th)*" (Odell 2004, p. xxiii).

While Odell does not deny that the production of oil will peak at some point in time, he does not expect the oil industry to reach that peak soon. In Odell (2004), he projects conventional production to peak around 2030, but due to the increasing share of non-conventional production, overall oil production is forecasted to reach its peak not before 2060. Even after that point in time, the declining usage of oil will be rather driven by lack of demand than by availability constraints: "*The world will not be running out of oil, or even out of the ability to extend supply* […] *Oil could instead be running out of markets in the face of increasing competition of gas*" (Odell 2004, p. 53).

Like other Cornucopians, Odell considers the viewpoint of the Neo-Malthusians, to whom he refers as "*Flat Earthers*", as a result of a static misinterpretation of the concept of resources and reserves. In his opinion, the Neo-Malthusian approach is falsely based on the assumptions that no new major oil deposits can be discovered as the entire world is nearly fully explored and that production technology will not advance significantly further. In total, this perceptions adds up to a "*'flat earth theory' in which the sciences and technologies of oil discovery, development and exploitation are at the edge of that world*" (Odell 2004, p. 46). However, as no long-term rising resource price can be observed, Odell dismisses this view. Looking back over the last 30 years, in which global proven oil reserves have increased despite ongoing production[25], Odell (2004) concludes that the world "*was 'running into oil' rather 'out of it'*" (p. 36).

The proposal to backdate updated estimates of oil field sizes to their initial date of discovery as proposed by Campbell and Laherrère (1998) as well as Campbell and Sivertsson (2003) (cf. subsection 4.2.1.3) is also discarded by Odell (2004). While the Neo-Malthusian school of thought applies this approach to prove that oil production is already beyond its peak, Odell sees this methodology as inappropriate to project future supply volumes. First, he argues that the date is not relevant at all, only the volume is the data that matters. Second, backdating resource volume updates incorrectly mingles data based on different technologies, different market prices and different production cost.

4.2.3 Summary and implications for this thesis

The comparison of the two dominant schools of thought for availability of natural resources has shown that they are as controversial as possible. On the one hand are the Neo-Malthusians, who clearly affirm the scarcity of natural resources and even forecast depletion in the mid- or even near-term future. On the other hand, the Cornucopians, predominantly economists, are convinced that depletion will never become a pressing issue because market forces will regulate demand and also will create incentives for higher efficiency and the development of alternative energy sources.

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[25] Odell (2004) also refers to a scientific debate regarding the origin of oil. Gold (1992), (1993) and several authors from the Former Soviet Union discuss the possibility of oil being a renewable resource, as the result of abiogenic processes. Following their argumentation, oil is being produced continuously in the pre-Cambrian crystalline basement and does not originate from organic material. They support this view with calculations that, especially for giant oilfields, the available organic materials were not sufficient to form that large oil deposits. Cf. Glasby (2006) for a review and discussion of the two major theories on abiogenic oil and gas origins.

The debate is primarily focused on crude oil, being the fuel with the greatest importance for the global economy. Up to a certain degree, also natural gas is being discussed whereas for hard coal and lignite the proven reserves are at least so large that fears for depletion are not that pressing.

Obviously, it is hard to decide which school of thought “is right”, as both sides have good as well as weak points in their argumentation lines. Intuitively, a finite amount of natural resources seems to be the correct answer but history has proven the arguments of the Cornucopians to be right – at least for the time being.

However, it is not the purpose of this thesis to judge whether we will run out of fossil fuels at some point in the future. Instead, based on the above discussion, the working hypothesis for the further chapters is that the world will not face depletion of any fossil fuel during the period under consideration, but maybe at some point later in time. This view corresponds with the assessment of Hatamian (1998): “*Within the next few decades, fuel availability is not in itself likely to be an important determinant of fuel choice*” (p. 58). Also, Ströbele (1987) advises not to treat the remaining resource volume as exogenously given but as a stochastic variable, fluctuating around an average value. He concludes that, based on this approach, “*numerous resource economists apply a concept of in principle unlimited resource stocks*” (Ströbele 1987, p. 59).

Assumptions about the availability of fossil fuels are crucial for the assessment of long-term prices on multiple dimensions. The importance of this discussion cannot be emphasized enough. Conclusions drawn from this chapter will significantly impact both the subsequent theoretical review of price key drivers, particularly on the supply side, as well as the specifications of the empirical model. Chapter 5 will look into these aspects in detail.

5 LONG-TERM PRICE FORMATION OF FOSSIL FUELS

Market prices of fossil primary fuels are influenced by a broad range of key drivers both on the supply and on the demand side. Some of these drivers can be considered as relatively stable and are most likely to change only gradually with moderate effects on market prices. Other drivers can change quite abruptly with immediate and significant impacts on market prices. Geopolitical events are one of the most obvious examples here, triggering fluctuations especially in the price of crude oil.

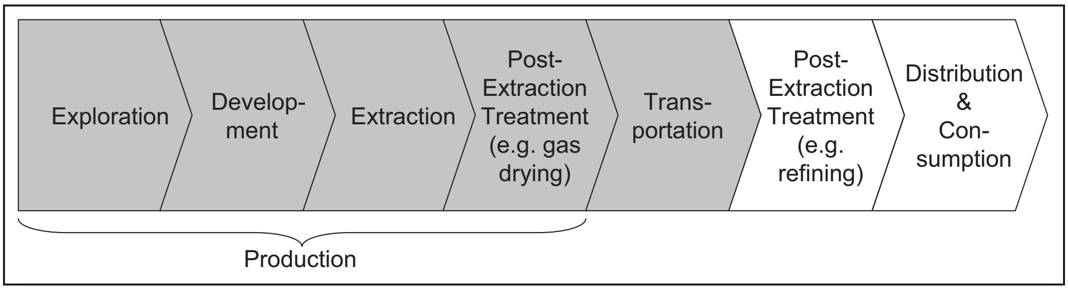
All key drivers comprise elements of uncertainty specific to each individual driver. First, it is uncertain whether a change of the status quo will occur at all, second, when it will appear, and third, how much a change of this specific driver will alter the overall market price of one or several fossil fuels.

This chapter aims at providing an overview on the most important drivers of fossil fuel market prices and gives a qualitative assessment of the uncertainties related to each driver. The objective is to provide a comprehensive overview on all possible key drivers relevant for fossil fuel prices. Besides a purely descriptive discussion of the possible impact of the key drivers on fossil fuel prices, the relevant theoretical models are also discussed to describe the interdependencies between key drivers and fuel prices in a consistent way. So while the primary approach is heuristic and phenomenological to cope with the variety and complexity of reality, the relevant theoretical underpinnings are not discarded but discussed where appropriate. Still, the formulation of some uniform, integrated theory is not attempted at this stage. This will rather be the task of chapter 7. Not all drivers and uncertainties introduced here will be considered in the model due to data and complexity restrictions. Nevertheless, all major drivers are introduced in this chapter for the sake of completeness.

Sections 1 and 2 describe the drivers and uncertainties on the supply and demand side respectively. Of course, there are always interdependencies between supply and demand sides and one side cannot be considered without considering the other. Certain key drivers can be predominantly attributed to one side, e.g. scarcity to the supply side or demand elasticity to the demand side. Still, some key drivers described in section 3 cannot be solely allocated to supply or demand alone. For example, a backstop technology will influence scarcity rent even prior to its introduction and demand patterns after its introduction. For that reason, some key drivers will be mentioned several times in the following sections, describing their respective impacts.

5.1 Fuel prices and related uncertainties from a supply perspective

Looking at the supply chain for fossil fuels (cf. Fig. 5-1), this thesis focuses on all costs that occur until the fuel is delivered to either national or international wholesale markets, i.e. production and transportation costs are considered. Costs that occur after the initial transaction between fuel supplier and wholesale customer, e.g. costs for refining or distribution, are not dealt with further.



Source: Own representation

Fig. 5-1: Fossil fuel supply chain steps considered in this thesis

Supply costs are among the most obvious key drivers for fossil fuel prices. Two other important key drivers on the supply side are scarcity rent and the impact of cartelization. These however cannot be located exactly in the supply chain, as they may occur across several steps. However, they too can contribute significantly to world market price levels.

Significant uncertainties are associated to all key drivers and must not be neglected when considering future developments of fossil fuel prices. "*Uncertainty is prevalent in decision making regarding non-renewable resource extraction and use. There is uncertainty, for example, about stock sizes, extraction costs, […] pay-offs from exploration for new stock, and the actions of rivals*" (Perman, Ma et al. 2003, p. 526). Therefore, for all drivers considered, a qualitative assessment of the relevant uncertainties will be made.

The first two subsections on scarcity rent and marginal costs of production in particular take the Hotelling rule (cf. Hotelling 1931) as starting point. This framework has been chosen due to its historic relevance and also its simplicity. Still, it has a number of shortcomings and insufficiencies that will also be addressed in this chapter. Also, enhancements of the Hotelling rule and alternative frameworks on price formation of fossil fuels are presented. It needs to be emphasized that the Hotelling rule is a theoretical framework that has not been proven to be reflected in real world market price behavior (cf. discussion of validity in section 5.1.1). As explained below, there are multiple effects outside the Hotelling model that may superpose the postulated effects. However, for the introduction of the key drivers based on ceteris paribus analyses, the Hotelling rule is a helpful instrument. Wherever appropriate, objections to Hotelling's concept are discussed. Also, an alternative approach by Adelman (1993), (1995) is introduced to reflect the discussion on resource availability from section 4.2.

5.1.1 Scarcity

Simon, Weinrauch et al. (1994) identify four indicators for increasing scarcity of natural resources: increasing prices over time, decreasing stock sizes (especially proven reserves), decreasing reserve-to-production ratio and decreasing production over time. Not all of the indicators need to occur at the same time. For example, if the production level of a given natural resource has not still reached its peak, the production rate will not decline from one period to the next. Still, the natural resource may be very well scarce. On the other hand, declining production alone can have other reasons than scarcity, e.g. the growing importance of a substitute good. To indicate scarcity in this case, market prices need to rise simultaneously.

Simon (1991a) also elaborates on how scarcity is generally perceived differently by economists and engineers: "*Economists generally view the expenditures in physical or money terms necessary to obtain a good, relative to some other quantity of expenditures, as the appropriate measure of scarcity. This is in contrast to measuring scarcity with an actual or hypothetic estimate of physical quantities that are thought to 'exist', as technologists are wont to do.* […] *The price of natural resources relative to wages is, in my view, the best measure of scarcity with respect to human welfare*" (p. 25). At least in part, this also provides an explanation why the debate between Neo-Malthusians and Cornucopians (cf. section 4.2) is so intense and irreconcilable: The understanding of the term scarcity itself differs among the parties.

When a natural resource is perceived to be scarce, scarcity rent can be an important element of the observed market price. Scarcity rent is based on the intrinsic value of a natural fuel or resource solely due to the fact or perception that it is scarce or of limited availability. The most prominent approach for the prediction of a scarcity rent and the optimal intertemporal allocation of a limited stock of natural resources is the Hotelling rule (cf. Hotelling 1931 and Darnell (ed.) 1990). As a second established concept, the work of Adelman is discussed separately.

5.1.1.1 Scarcity as cornerstone of the Hotelling rule

As described by Ströbele (1987) and Hensing, Pfaffenberger et al. (1998), the Hotelling model in its simplest form is based on an idealized scenario where the demand function for the current and all future periods is given, the size S_0 of the deposit is perfectly known, extraction costs do not accrue and forward contracts can be signed for all future periods. The interest rate r is constant for all time periods and the market price p is exogenous and identical for all resource owners. While all these prerequisites are assumed to be appropriate in a first step, they will be alleviated one after the other to approximate real world conditions.

The question for each market participant is whether the profit-maximizing strategy is to produce an additional unit in the current period $t=0$ or to postpone the production to later periods $t>0$ when a higher price per unit can be realized.

If the net present value of a unit produced at some point in the future is expected to be lower than that of a unit produced today, the profit-maximizing strategy (not considering technical capacity constraints) would be to exploit the entire deposit immediately. As a result, the fuel becomes scarce in the future. Thus, its future price and consequently its net present value rise until a balance between current and future production and price levels is reached.

If the net present value of a unit produced in the future is higher than the current market price, all production would be postponed to that point in future. This would drive down the future price until the imbalance between current and future discounted prices is no longer existent. As a result, a stable equilibrium is reached in both cases where the net present value of the natural resource's price in any future time period equals the current price (cf. Ströbele 1987).

In other words, the price $p(t)$ grows with the interest rate[26] r used for the calculation of the net present value:

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[26] Also cf. Farzin (1984) who argues that a change of the interest rate has two effects: On the one hand, a lower interest rate will lead to a “conservation effect“, making a production postponed into the future more attractive. On the other hand, a lower interest rate reduces the cost of capital investments required for production and/ or consumption of the resource, which might lead to an increase in production and demand. Farzin (1984) calls this the “disinvestment effect“. The net effect depends on the degree of capital intensity of the production and on the size of the resource stock. For example, a low interest rate in an environment with a high degree of capital intensity will override the conservation effect and lead to increased production of the resource.

$$p(t) = p_0 \cdot e^{r \cdot t} \tag{5.1}$$

In literature (cf. e.g. Dasgupta and Heal 1979, Ströbele 1987 and Perman, Ma et al. 2003), a finite time horizon of natural resource consumption is introduced in order to explain better certain aspects of the Hotelling model. By assumption, the natural resource under consideration will not be of any significant value beyond a certain date T_B in future. It is postulated that at T_B a *backstop technology*[27] will replace current technologies and thus will dramatically reduce the demand for the natural resource. Initially, the costs per comparable unit of the backstop technology p_B are higher than the price $p(t)$ of the natural resource. As such, the backstop technology will be held in reserve until the natural resource is completely depleted or until the costs of the new technology have dropped below the resource price (cf. Dasgupta and Heal 1979 and Levy 2000).

Since the introduction of such a backstop technology dramatically reduces the value of natural resources not extracted until then, an optimal extraction policy both for the individual resource owner and on a global scale needs to ensure that the stock of producible natural resources is depleted exactly when the resource price $p(t)$ reaches p_B. The price increase over time will be determined by the interest rate r as given by the Hotelling rule. This leaves only the initial price p_0, i.e. the current price, as lever to adjust the price path in a way that the above condition is met (cf. Fig. 5-2).

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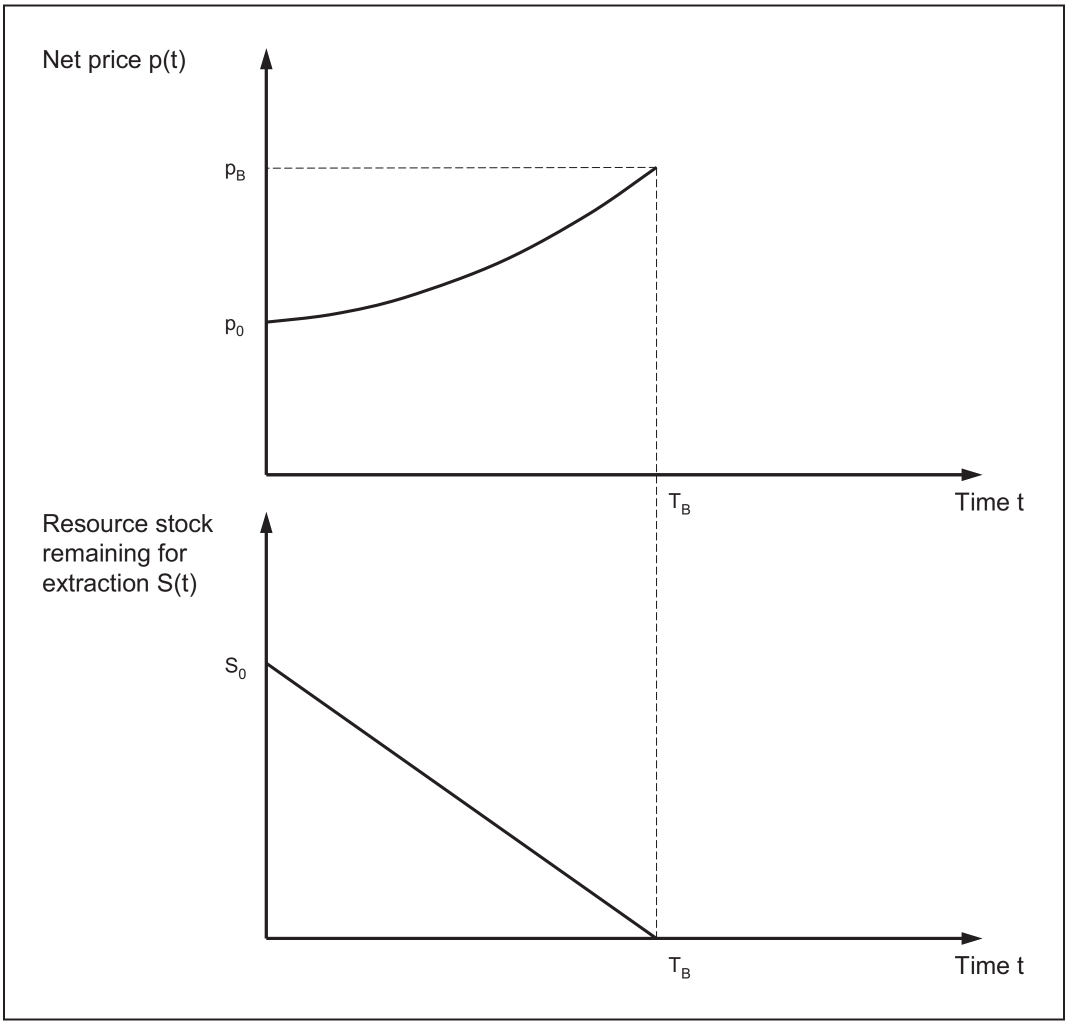
[27] A backstop technology is a technology suitable to produce a substitute good for a limited natural resource without facing (at least temporarily) similar resource restrictions (cf. Nordhaus, Houthakker et al. 1973, p. 532).



Source: Own representation based on Dasgupta and Heal (1979), p. 153ff., and Perman, Ma et al. (2003), p. 486ff.

Fig. 5-2: Impact of backstop technology on net price and extraction

Dasgupta and Heal (1979) argue that resource owners rather lean towards too high net prices than towards too low prices. Prices below the optimal level and, linked to that, an accelerated extraction rate make the owners aware that the natural resource might be depleted too soon, i.e. before T_B. Charging too low prices, they would miss out on possible profits. As soon as they realize the wrong pricing, resource owners and traders will start to hoard the natural resource to profit from an expected price increase. In the end, this would readjust the price to the price path as postulated by Hotelling. Contrary to that, Dasgupta and Heal assume mine owners to be too myopic to recognize the possibly foregone profits from too high prices. Due to the long time span usually left until resource depletion or introduction of a backstop technology, market participants might not be able to see that the resource stock will not be entirely depleted at T_B and therefore will not take corrective actions. The large number of key drivers in combination with the huge size of deposits (i.e. a high reserve-to-production ratio) and long technical lifespans of technologies both on the supply and demand side make it virtually impossible for decision makers to compile sufficient data that would justify the assumption of perfect foresight: "*The reason why pricing of resources might be myopic is that very few planners have the ability, or perhaps even the desire, to check consistency for several decades*" (Nordhaus, Houthakker et al. 1973, p. 536). In summary, if there is a deviation from Hotelling's equilibrium price path, it is more likely to be an upward than a downward deviation.

Hensing, Pfaffenberger et al. (1998) point out that, despite its simplicity and limitations, the Hotelling model explains two main characteristics of non-renewable natural resources: First, scarcity alone is an important factor of a product price greater than zero, even with extraction costs assumed to be negligible. Second, future prices will rise with the market interest rate. But "*all efficiently managed assets will satisfy the condition that their discounted prices should be equal at all points in time*" (Perman, Ma et al. 2003, p. 485) so that the Hotelling rule does not reveal any particularities of natural resources at this point.

Contrary to the above view, Adelman (1995) finds it "*impossible to reconcile these data* [historical oil prices] *with any theory or vision that oil is a 'limited exhaustible resource', becoming ever more scarce and expensive*" (p. 292). In his review of world oil prices after World War II until 1985, he concludes that increasing knowledge and improving technology of oil production had outpaced any symptoms of scarcity, like smaller deposits and poorer quality. His alternative framework is discussed in some more detail further below.

Also Lynch (2002) disputes the inevitability of rising prices due to a scarcity effect in general. In his review of various attempts to forecast oil prices between 1982 and 1991, he argues that despite an average assumed annual growth rate of prices between 3.6 and 4.6 percent in the forecasts, observed prices decline by 2 to 3 percent per year in real terms. Barnett and Morse (1963) come to similar results for natural resources in general. They analyze the development of prices and costs in agriculture, forestry, fishing and minerals from 1870 to 1957 in the United States. With regard to extractive products, they observe both for market prices and production costs a decline over the period under consideration. Based on these results, they reject the hypothesis that natural resources are becoming increasingly scarce since at least prices or costs should rise in such a case. Despite its age, this analysis from Barnett and Morse supports Lynch's view that fossil fuel prices do not necessarily rise at the market interest rate over time. It could be concluded that either the Hotelling rule does not accurately describe reality or that there are other key drivers superposing the impact of an increasing scarcity rent.

A domination of other drivers over the scarcity rent is most likely when the remaining stock actually is or at least is considered to be so large that the market participants do not regard scarcity as a limiting factor for the near- or mid-term future. Since market participants tend to be myopic and base their production, investment and consumption decisions rather on the outlook for the next 5 to 10 years than for the next 100 or more years, a real or perceived abundance of an exhaustible resource will significantly reduce the importance of scarcity rents for price formation processes. For example, this was the case for oil in the years prior to the first world oil crisis in 1973.

However, if scarcity does get more and more pressing, scarcity rent is likely to become the dominating factor. Simmons (2005a), convinced that oil production is nearing or even has reached its peak, regards scarcity as the key driver of future oil price developments: "*Once oil supply peaks and begins to decrease, the scarcity factor alone will force oil prices to far higher levels than today's perceived 'high prices'*" (p. 344).

Perman, Ma et al. (2003) review several empirical studies, including the one from Barnett and Morse (1963), who try to test the predictive power of the Hotelling rule based on historical time series of prices. They conclude that "*there is no clear picture of whether resource prices typically rise or fall over time. We can no more be confident that the theory is true than that it is not true - a most unsatisfactory state of affairs*" (p. 528).

In their search for an explanation, they highlight the fact that the Hotelling rule only refers to the *net price* of the resource, i.e. the royalty paid to the natural resource owner. As observable market prices include other components besides royalty, e.g. costs of production and transportation, they cannot be used as data points to validate the Hotelling rule. Consequently, falling market prices over time are not necessarily a proof for the inaccuracy of the Hotelling rule.

The net price or royalty itself is not directly observable. The construction of a proxy measure may cause several methodical and statistical problems which shall not be further dealt with at this point. However, even tests with net price movements did not lead to unanimous results in favor or against the validity of the Hotelling rule (cf. Perman, Ma et al. 2003). For example, Devaranjan and Fisher (1982) present a model in which they use marginal exploration costs as observable data points. They define scarcity as “*difference in the cost of providing oil today and the cost of providing it in the future*” (p. 1289). Since they observe a slight increase in exploration costs from 1946 until 1971, while at the same time oil prices have been rather decreasing, also marginal exploration costs do not qualify as unconditional indicator of scarcity.

Pindyck (1978b) proposes different scarcity measures for the mineral in situ and for the mineral as production input. In the former situation, he recommends *rent* as scarcity indicator, which he defines as the difference between market price and marginal extraction cost[28]. This measure is deemed appropriate for in-situ resources as it does not include extraction, transportation and external costs, e.g. damage caused to the environment. For the latter case, the market price of the resource is regarded as more appropriate because it now includes all relevant costs.

It is obvious that already in an ex-post analysis the Hotelling rule faces severe limitations. Its predictive power depends on the extent of the uncertainties linked to the assumptions made.

First, whether scarcity is an urging problem or not is determined by the total amount of the natural resource remaining for extraction, i.e. the Ultimate Recoverable Resources less the cumulative production up to this date. As demonstrated in chapter 4, URR figures alone are highly uncertain data depending on various inputs, e.g. technological advance and market price level, and can repeatedly be subject to changes. In other words, even in a static setting without new resource discoveries, the remaining stock size is an uncertain number and does not provide a solid basis for scarcity rent calculation as required by the Hotelling rule.

Second, the degree of uncertainty is significantly increased if the remaining stock size is allowed to change, e.g. due to new discoveries or reassessment of existing deposits. Pindyck (1980) reasons that “*for most resources, however, the greatest uncertainty is over how reserves will change in the future - that is, what effective recoverable reserves will be over the lifetime of resource use*” (p. 1205). According to the Hotelling rule in combination with the assumption of a backstop

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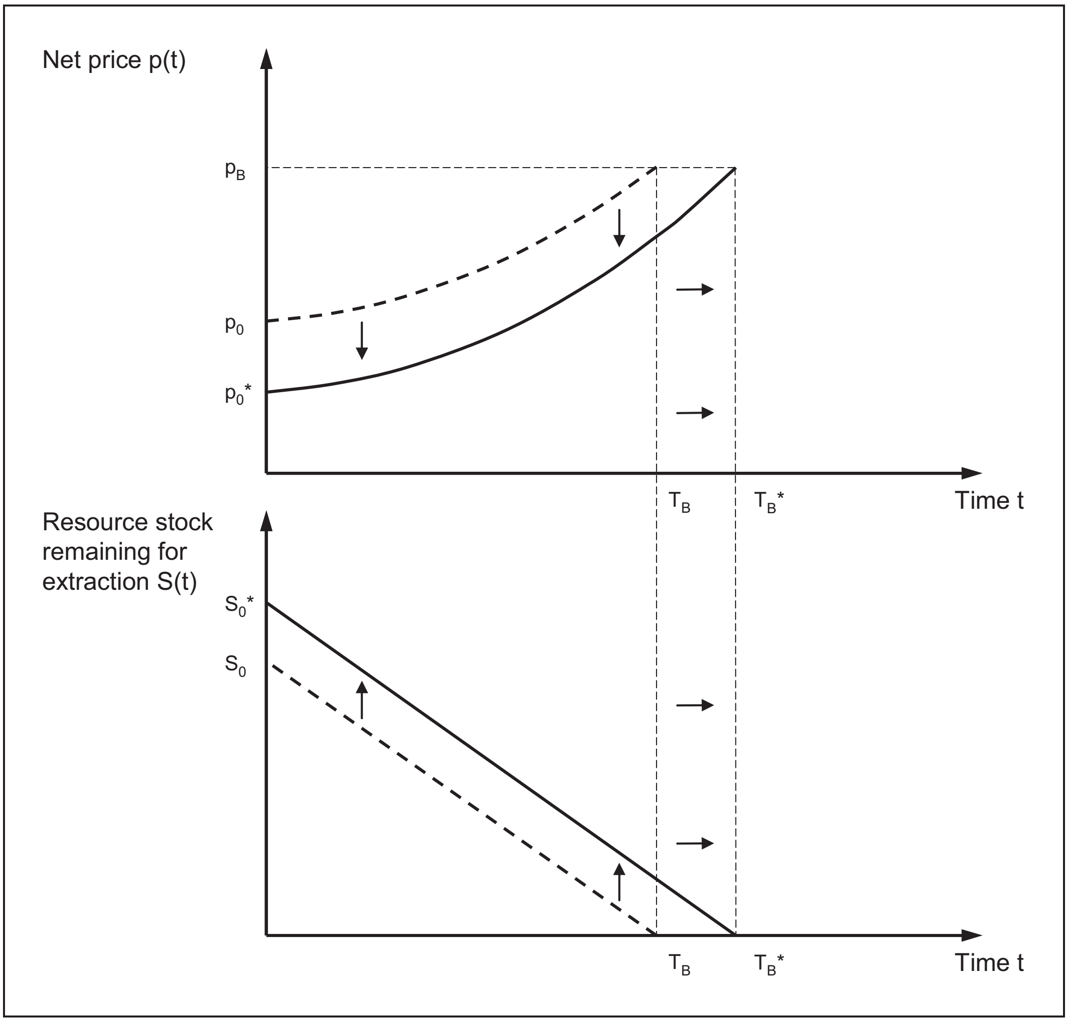
[28] This definition is valid for competitive markets. For monopolistic markets, rent is defined as the difference between marginal revenue and marginal extraction cost (cf. Pindyck 1978b, p. 854).

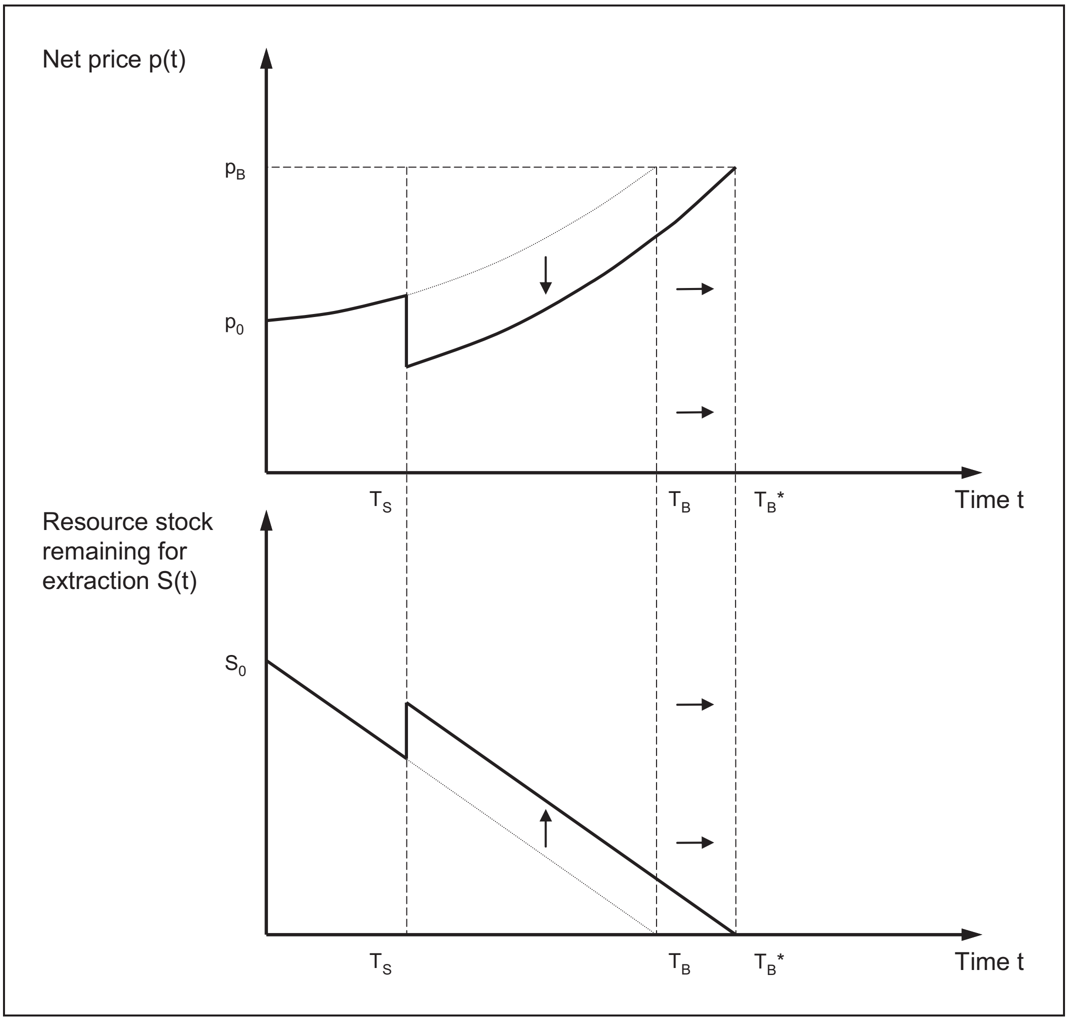
technology, a change of URR in *t=0* must ceteris paribus lead to a readjustment of the initial resource net price p_0. If the URR rises, net prices must fall accordingly and vice versa. The rationale behind the decrease in royalty is the following: If the remaining stock size turns out to be larger than previously assumed, but the royalty remains unchanged, the demand for the natural resource would remain the same. Consequently, when the net price reaches the unit price of the backstop technology (i.e. $p(t)$ equals p_B) the stock has not been fully depleted and the resource owners have not realized the entire possible profit. To avoid that, the resource owners must lower the initial net price p_0 to foster demand (cf. Perman, Ma et al. 2003). An increase in stock size decreases the initial net price from p_0 to p_0^* and postpones the introduction of the backstop technology from T_B to T_B^* (cf. Fig. 5-3). It should be kept in mind that the assumption of negligible extraction costs is still maintained.



Source: Own representation based on Perman, Ma et al. (2003), p. 521

Fig. 5-3: Impact of stock size increase in *t=0*

It follows that the question as to whether the stock size will be revised and to what extent is one of the key uncertainties impacting scarcity rent. If the revision of the stock size does not occur in $t=0$ but at some point in time $0<T_S<T_B$ in the future, a discontinuous adjustment of the net price will take place, as depicted in Fig. 5-4:

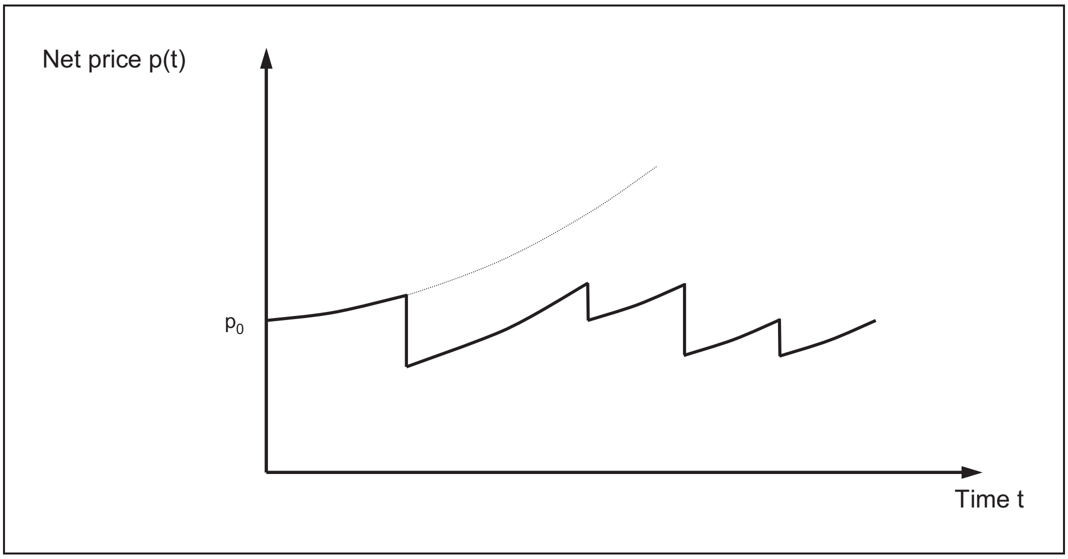


Source: Own representation based on
Perman, Ma et al. (2003), p. 521ff.

Fig. 5-4: Impact of unanticipated stock size increase in $t=T_S$

It is important to note that such a pattern will only occur if the adjustment in $t=T_S$ had not been expected previously, i.e. was unknown in $0<t<T_S$. Otherwise the market participants would have adjusted their selling and purchasing patterns and consequently the price path prior to the actual announcement of the stock size revision.

If there are several instead of only one unexpected upward adjustments of the stock size, the net price development will look similar to the pattern in Fig. 5-5:

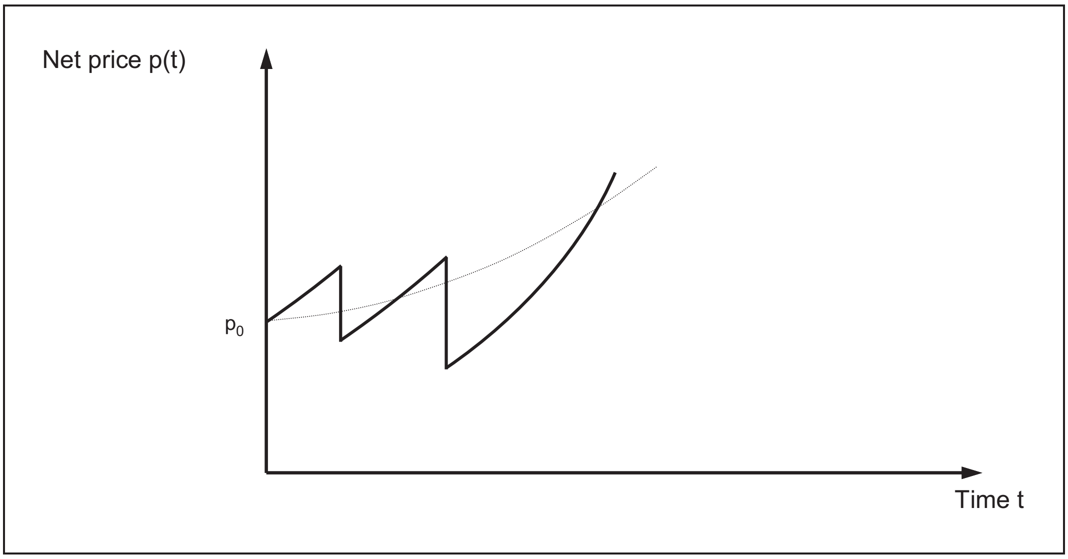


Source: Own representation based on
Perman, Ma et al. (2003), p. 522

Fig. 5-5: Impact of several unanticipated stock size increases in *t>0*

As Perman, Ma et al. (2003) note, oil prices actually show the pattern depicted in Fig. 5-5. Also, this approach provides an explanation why net prices can decline over time without violating the Hotelling rule. Again, it is important to remember that both the extent of the price adjustments, depending on the size of additionally discovered amounts, as well as the timing of adjustments are uncertain variables.

Dasgupta and Heal (1979) go even one step further. They argue that, due to this uncertainty, natural resource owners that have been holding the resource prior to upward stock revisions suffer from capital losses on their property due to the price decrease. To compensate that, they are inclined to raise the royalty at a rate higher than the sure interest rate as postulated by the Hotelling rule. The rationale behind this behavior is the owners' attempt to effectively realize the same rate of return to their stocks as they would without new discoveries. Fig. 5-6 shows the resulting price path.



Source: Own representation based on
Dasgupta and Heal (1979), p. 468

Fig. 5-6: Impact of several unanticipated stock size increases in *t>0* with higher interest rate

The degree of uncertainty about the size of URR can be reduced by conducting exploration activities. Without going too deeply into details about exploration methodology and technology[29], it can be said that exploration alone is a broad field with many immanent uncertainties. These uncertainties are primarily of geological and geophysical nature, e.g. location, depth, amount and quality of the deposit. Exploration activities will only be able to reduce the URR-related uncertainties but can never create a situation of perfect certainty.

While the exploration-related technical uncertainties will not further be highlighted here, the timing of individual exploration activities is another important decision variable for each resource owner, as explained by Dasgupta and Heal (1979). It is assumed that in *t=0*, each market participant has the same set of information about the current estimate of remaining stock size available for exploitation. The net price of the natural resource rises at the market interest rate. Exploration activities can be undertaken by each market participant at his own costs at any time. The additional information gain from exploration accrues directly only to the market participants paying for the activities. Considering the costs, it would be optimal for each market participant not to perform any exploration or at least to postpone it as long as possible to minimize the net present value of the costs.

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[29] Cf. Simmons (2005a) for a explanatory summary of oil exploration activities.

But proprietary additional information about stock sizes would allow for profit maximization at the cost of less well-informed market participants. If a mine owner knows ahead of all others that the stock sizes are larger than commonly assumed, he also knows that current prices are too high and will experience a downward revision as soon as this becomes publicly known. Before this happens, he will try to sell as much as possible of his stock for profit maximization. Vice versa, he will try to save as much as possible of his stock if he knows that URR figures have been overestimated in order to profit from a coming abrupt price increase.

From this point of view, there is also an incentive to conduct exploration activities as early as possible to gain a competitive advantage over the competitors. However, if all market participants follow this rationale, all get the same new information at the same time and nobody will be able to benefit from it. The same happens if a mine owner with proprietary information tries too obviously to benefit from this information. Other market participants will be able to observe his behavior, make the right conclusions and adjust their own trading pattern accordingly. The following price change reduces the benefit of the exploration pioneer who has to bear all the exploration-related costs.

5.1.1.2 Adelman's objections to scarcity as limiting constraint

While the points of criticism discussed so far primarily focused on the relative importance of scarcity and the implementation into the Hotelling framework, Adelman objects the concept of scarcity in general (also cf. subsection 4.2.2): "*The price has no relation to scarcity, present or future. Long-term marginal cost, even with an excessive allowance for resource rent or user cost, remains a small fraction of the price*" (Adelman 1993, p. 2).

Based on his conception of fossil fuels as unlimited resources, Adelman dismisses the assumption that values of resources in situ increase with the interest rate over time. All other parameters being equal, continuous production and consumption of fossil fuels should not have any effect on current and future prices. Instead, only production costs determine the value of resource deposits: "*The value of a barrel in the ground paralleled the cost of developing the barrel into a reserve. This is necessary because developing a barrel is a substitute for buying one*" (Adelman 1995, p. 289).

Adelman (1990) also develops his own model incorporating the above statements. His key conclusions are that the assumption of a fixed resource stock is not valid and not required to model resource consumption. Costs for the development of a deposit are positively correlated with costs for exploration and discovery. Consequently, required investment per unit of added reserves or added production capacity is a good indicator for resource scarcity. Contrary to the classic Hotelling approach, the discount rate does not affect the value of minerals in situ nor the optimal depletion rate.

As Adelman observes neither increasing investment costs per unit of added reserves or capacities nor long-term increases in crude oil prices but only short-lived spikes, he concludes that production costs and thus scarcity are not increasing over time.

The fact that Adelman rejects the assumption of a fixed resource stock does not mean that he discards the Hotelling approach in general: "*Once we discard the false assumption of a limited stock, we can see Hotelling's great contribution: to reduce the vague notion of 'resource scarcity' to an observable economic fact: the present value of a unit of inventory, subject to the same errors as any other asset values*" (Adelman 1993, p. 8).

In the end, the answer to the question whether availability and scarcity are important cost drivers for fossil fuels or not, is primarily driven by the affiliation to one of the schools of thought from chapter 4. Neo-Malthusians are likely to regard scarcity as the most important key driver on fuel prices whereas Cornucopians tend to reject any influence of availability on prices and refer to other cost drivers discussed in the remaining part of this chapter as key price components. As the empirical foundation of such a choice is limited, a pragmatic approach is to consider different levels of fuel availability and treat their occurrence as stochastic variables. Assumptions regarding the importance of scarcity of resources at the end of the considered time horizon can be implemented by adjusting the terminal value per unit.

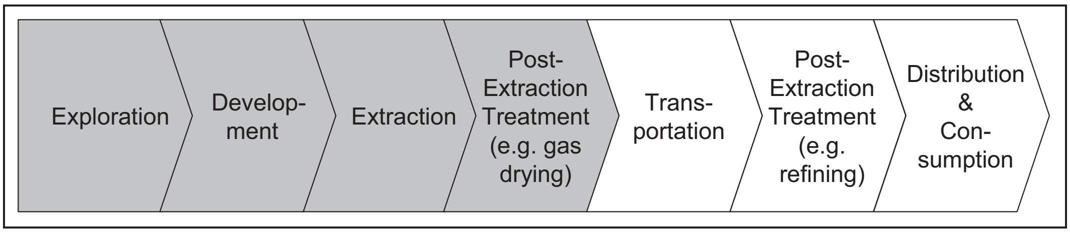
5.1.2 Marginal production costs

In subsection 5.1.1, production costs have been assumed to be negligible in the context of the Hotelling framework. Although this assumption has been helpful to introduce this concept, it obviously is not consistent with reality. Consequently, in a next step production costs are included in the analysis and also the related uncertainties will be discussed. It needs to be kept in mind that the following conclusions are not in line with the work of Adelman, Simon and other Cornucopians.

Their view on the influence of production costs is discussed at the end of this subsection.

Pricing of natural resources is related to the production costs of the last unit produced[30]. Dasgupta and Heal (1979) refer to this relationship as "*extremely complicated*" (p. 169).

Production costs can be categorized by various criteria. Looking at the fossil fuel supply chain (cf. Fig. 5-7), production costs accrue for exploration, development, extraction and post-extraction treatments prior to transportation.



Source: Own representation

Fig. 5-7: Production-related costs in fossil fuel supply chain

Without going too deep into the technical aspects of fossil fuel production, exploration refers to the activities related to the search and discovery of new fields, including geological analyses and the drilling of exploration wells[31]. Development describes the transformation of detected fields into exploitable deposits. Extraction relates to all activities of getting the resource out of the ground. For oil, Masseron (1990) estimates that 10 to 20 percent of total production expenditures can be allocated to exploration activities and 40 to 60 percent to field development. The remaining 20 to 50 percent account for extraction costs (cf. Masseron 1990, p. 98f.).

Post-extraction treatment refers to further processing steps of fossil fuels, e.g. crude oil refining or natural gas drying. For purposes of this thesis, post-extraction costs are only relevant if they occur prior to the sale on the world market and are therefore included in the world market price. Transportation costs will be dealt with in 5.1.4.

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[30] Already after World War II, the seven major oil companies ("Seven Sisters") used the costs of the marginal barrel in the Gulf of Mexico as benchmark for their pricing system (cf. Campbell 1997b, p. 138).

[31] Cf. e.g. Pindyck (1978b) and Pindyck (1980) for a more detailed discussion of exploration costs and related uncertainties. The effects of exploration activities on the price level are described in the previous section of this chapter on scarcity.

Both for the discussion of key drivers as well as for specifications of the model, the distinction between exploration, development and extraction costs will not be maintained. All three cost types are subsumed under production costs, as opposed to transportation costs and post-extraction costs.

Another categorization distinguishes between fixed and variable costs of fossil fuel production. Fixed costs include all expenses that are not related to the level of output, e.g. capital costs and costs for general maintenance of equipment and facilities. Also license costs may fall into this category. Variable costs are comprised of all expenses that depend on the level of output, e.g. production labor cost, costs for replacement of utilization-dependent equipment wearout, energy cost, volume-dependent royalties or taxes as well as costs and opportunity costs related to improved and enhanced recovery (i.e. technical measures to increase the production rate or total volume in oil and gas production). This distinction is particularly important because the market's reaction to new URR data will depend on the part of already sunk costs. Hence, this has to be included in a comprehensive modeling approach.

5.1.2.1 Higher production costs from increasing depletion

For fossil fuel production, Perman, Ma et al. (2003) identify *rate of production* and *degree of depletion* or cumulative production as key cost drivers. The higher the rate of production, i.e. the higher the resource volume produced per time period, the higher the extraction costs per unit. A good example for this assumption can be found in Simmons (2005a): Since the 1950s, water injection has been used in Saudi Arabian oilfields to maximize the production rate. Contrary to conventional production techniques, where only natural reservoir pressure is utilized as long as possible, water injection technology has been used for some fields in Saudi Arabia right from the beginning of the fields' production lifecycle in order to increase output rates as much as possible. Clearly, such a program adds significantly to the unit cost of production compared to simple utilization of the natural pressure. A similar example can be constructed for coal mining where the faster depletion of a given deposit requires much greater investment than a low-speed production plan.

In addition to these higher costs that are primarily driven by throughput-related investments in technology, a higher production rate also creates opportunity costs related to foregone profits over a deposit's production lifecycle. Both Dasgupta and Heal (1979) and Simmons (2005a) point to the fact that excessive production rates reduce the overall production volume of any given resource deposit. This matter of fact, known as *overproduction*, is primarily relevant for the extraction of oil and natural gas. When the production rate is too high, the natural pressure of the reservoir decreases too fast and reduces the total amount of resource that can be recovered (URR). In other words, natural pressure fails earlier and more fuel is left in the ground than would have been at a lower rate of production. Technology, e.g. water injection, can only offset this loss of pressure to a certain degree, especially if it has been used right from the start of production. In his review of Saudi Arabian oil production, Simmons is convinced that the Saudi Arabian oil company Aramco had pushed its oilfields more than one time to the limits of production, causing perhaps irreparable damage, notably in the years prior to the nationalization of the company in 1973 and during the Iran Crisis from 1978 to 1981.

In principle, the same situation is possible for coal extraction. Trying to increase the production rate as much as possible, the mining company might focus on the major coal beds only and treat minor beds in between as excavation materials that otherwise would have been produced as well.

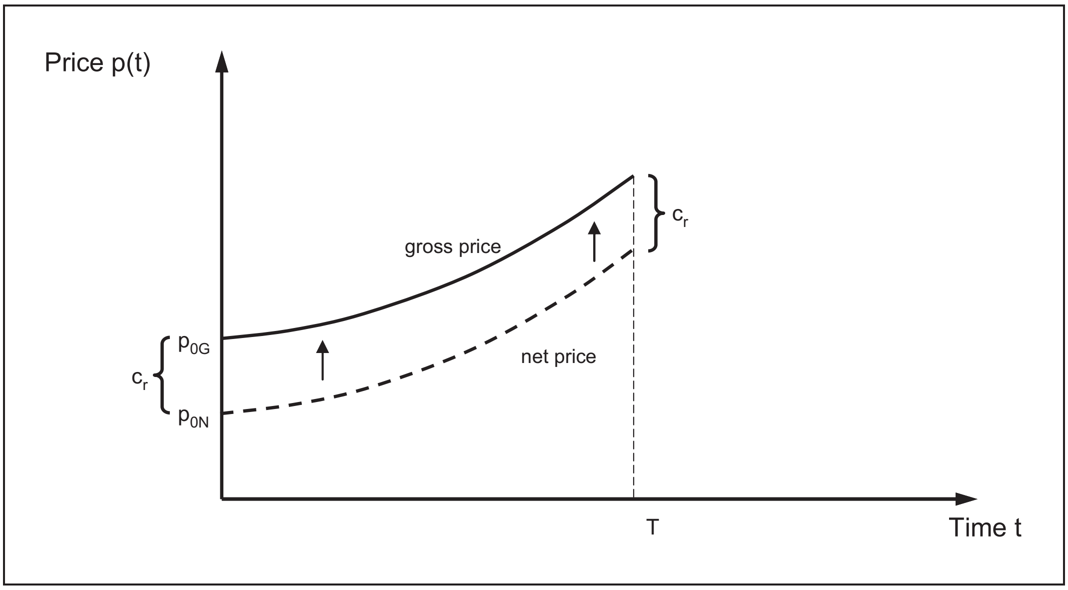
These production rate-related opportunity costs of overproduction are hard to quantify. It seems obvious that rate of production and opportunity costs are positively correlated. Due to Aramco's rigid information policy, Simmons is not able to further quantify this effect in Saudi Arabia, where the occurrence probably was most evident. Since going further into this problem would require significant technical and geographical data beyond the scope of this thesis, it will be not possible to include this aspect into the development of price paths in the following chapters. However, it should be kept in mind that overproduction can be a cost driver with significant mid- and long-term impact.

Total cumulative production or remaining stock size for depletion can also be an important driver of extraction costs. This can be explained by the example of a coal deposit. Initially, the coal is located close to the surface and the coal beds are broad and easily accessible. Production costs per unit of coal are comparatively low. As depletion increases, the miners have to dig deeper into the ground, the technical requirements for coal transport, air circulation and removal of water and excavation materials grow significantly and higher investments are required. Furthermore, the coal beds may get smaller and more distant from each other so that the volume of excavation materials that needs to be removed to mine one unit of coal increases. Also, high capacity technology cannot be used efficiently anymore. Regarding the order of production from deposits with different extraction costs, Solow and Wan (1976) show that it is optimal to exploit mineral deposits in the increasing order of production costs: "*No higher-cost resource can be used in an optimal program until all lower-cost grades have been exhausted*" (Solow and Wan 1976, p. 363).

A similar pattern can be observed for the costs of locating and developing new mineral deposits. Regardless of the type of resource, once the large fields have been found and exploited, it will require higher capital investment to find and produce from further, most likely smaller deposits. Since the easily accessible locations usually are found and exploited first, any further fields are typically located in more distant regions with geographically and geologically unfavorable conditions and are therefore more expensive to exploit on a per-unit basis. Based on these arguments, Perman, Ma et al. (2003) conclude that for non-renewable resources the per-unit extraction costs grow at an increasing rate.

In the previous subsection on scarcity rent, only the net price, i.e. the royalty paid to the owner, has been of interest. To allow for the inclusion of production costs, a *gross price* is introduced at this point. The gross price is identical to the market price and can therefore be easily measured whereas the net price is not directly observable.

Following the argumentation of Perman, Ma et al. (2003), of the two cost drivers mentioned above, rate of production and degree of depletion, only the former one has a direct impact on the gross price level p_G. The production rate-related marginal costs of extraction c_R are simply added on top of the royalty p_N and do not impact the net price's growth rate (cf. Fig. 5-8).



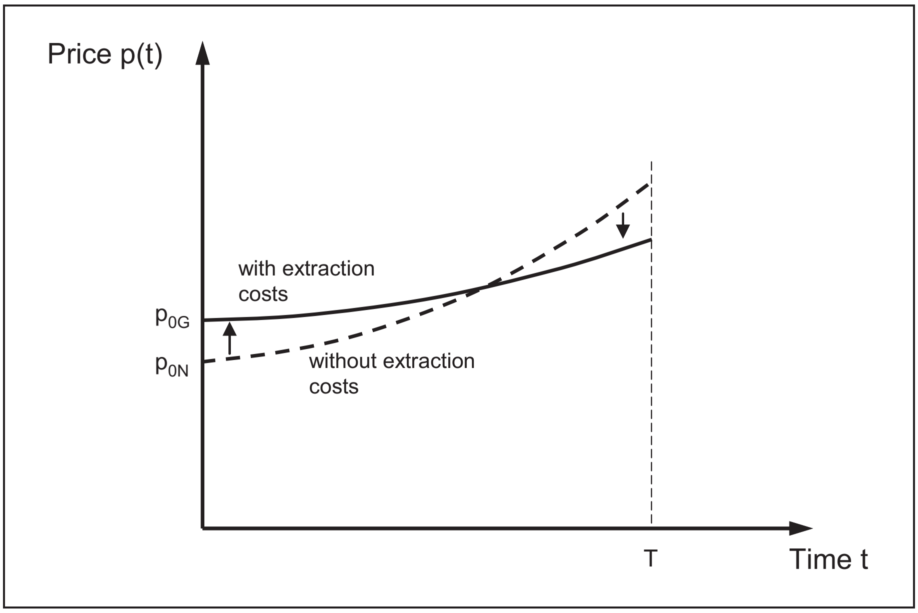
Source: Own representation based on Dasgupta and Heal (1979), p. 167ff. and Perman, Ma et al. (2003), p. 523f.

Fig. 5-8: Impact of production rate-related extraction costs on price

Costs related to the post-extraction treatment have the same impact on the gross price as shown above. Depending on where they accrue along the value chain, they will be added to the price prior to the sale (e.g. drying of natural gas) or will be borne by the buyer of the resource after the purchase (e.g. oil refining). They can be the trigger for significant market price fluctuations of the final product.

Contrary to that, the degree of depletion affects the rate of change of the net price p_N, i.e. of the royalty itself. This means that the increase of the net price does not equal the interest rate as postulated for non-existing extraction costs, but is lower than that. "*Efficient extraction over time implies that the rate of increase of the resource net price should be lower where extraction costs depend upon the resource stock size*" (Perman, Ma et al. 2003. p. 488). The reason for this phenomenon – which might seem counterintuitive at first sight – lies within the negative correlation between remaining resource stock and extraction costs. The increase of the net price which describes the growth in value of a resource unit not extracted in the current period but postponed to the next period is composed of the royalty – still increasing with the interest rate – and the avoided increase in extraction cost from not producing this additional unit. As these are avoided costs, the latter summand comes with a negative arithmetic sign. Hanson (1979) shows that a resource unit with high extraction costs has a lower present value at the same gross price than a unit with low extraction costs for two reasons. The first reason is that there are higher costs incurred for the production, and the second reason is that it is more efficient to postpone its production into the future (cf. Hanson 1979, p. 173).

The existence of costs correlated to the degree of depletion will thus slow down the growth of the net price. To compensate for that, the net price will be higher initially ($p_{0N}^* > p_{0N}$) but lower ultimately (cf. Fig. 5-9). A higher initial price also means that demand and therefore the rate of extraction will be lower initially but higher at the end of the extraction period compared to a situation where the extraction costs are negligible.



Source: Own representation based on Perman, Ma et al. (2003), p. 523f.

Fig. 5-9: Impact of depletion-related extraction costs on price

The future development of marginal production costs has been and will be significantly driven by production-related technological advances. Over the last decades, technological advancement has impacted price formation of fossil fuels on several dimensions. Through improvement of exploration methodologies (e.g. 3D seismic and magnetic exploration technology), it has been possible to locate previously unknown deposits that otherwise would have been difficult to find. This part of technological advance does not impact marginal costs of production directly but primarily leads to adjustment of the scarcity rent[32] (cf. Fig. 5-4 and Fig. 5-5).

Other developments, e.g. horizontal drilling, longwall mining and large-scale surface mining have helped to make the exploitation of deposits economically viable that otherwise would have remained untapped. Also a continuous increase in labor productivity contributed significantly. The combination of all effects allowed for an increase of the remaining recoverable stock and a reduction of the marginal cost of production. Last but not least, the same developments also benefited the exploitation of reserves already being mined. EIA/ DOE (1998) conclude that technological advances "*have revolutionized economies of scale in mining, marketing, and shipping coal in the large quantities required by electricity generation plants*" (EIA/ DOE 1998, p. 78).

Past decades and centuries have shown that advances in technology have a significant impact on the development of marginal costs of production. Thus, technological advance is one of the main sources of uncertainty for the future development of production costs. Dasgupta and Heal (1979) allude to the fact that although the world has experienced the introduction of various technical innovations in exploration and production equipment in the past leading to extended and cheaper natural resource production, this does not imply any data on the future development. In other words, it is highly uncertain whether the average historical pace of innovation will continue or not. Nevertheless, historical data provides a benchmark that should not be neglected. "*It is certainly dangerous to use past evidence and merely extrapolate into the future. It is at least equally dangerous to ignore past evidence totally and to rule out technical change*" (Dasgupta and Heal 1979, p. 206).

Deviations in either direction, i.e. both acceleration and slowdown of technological development, seem possible. In a review of future technology development, Hoyos (2004) comes to the conclusion that the progress in exploration techniques is unlikely to yield similar benefits as in the previous decades. For production techniques on the other hand, the U.S. Society of Exploration Geophysicists expects a dramatic increase of the possible oil recovery rates from 25 – 50 percent to 80 percent of URR and more within five years (cf. Hoyos 2004). However, whether this is a realistic assessment and how the different developments in exploration and production net out in the end remains an uncertain variable.

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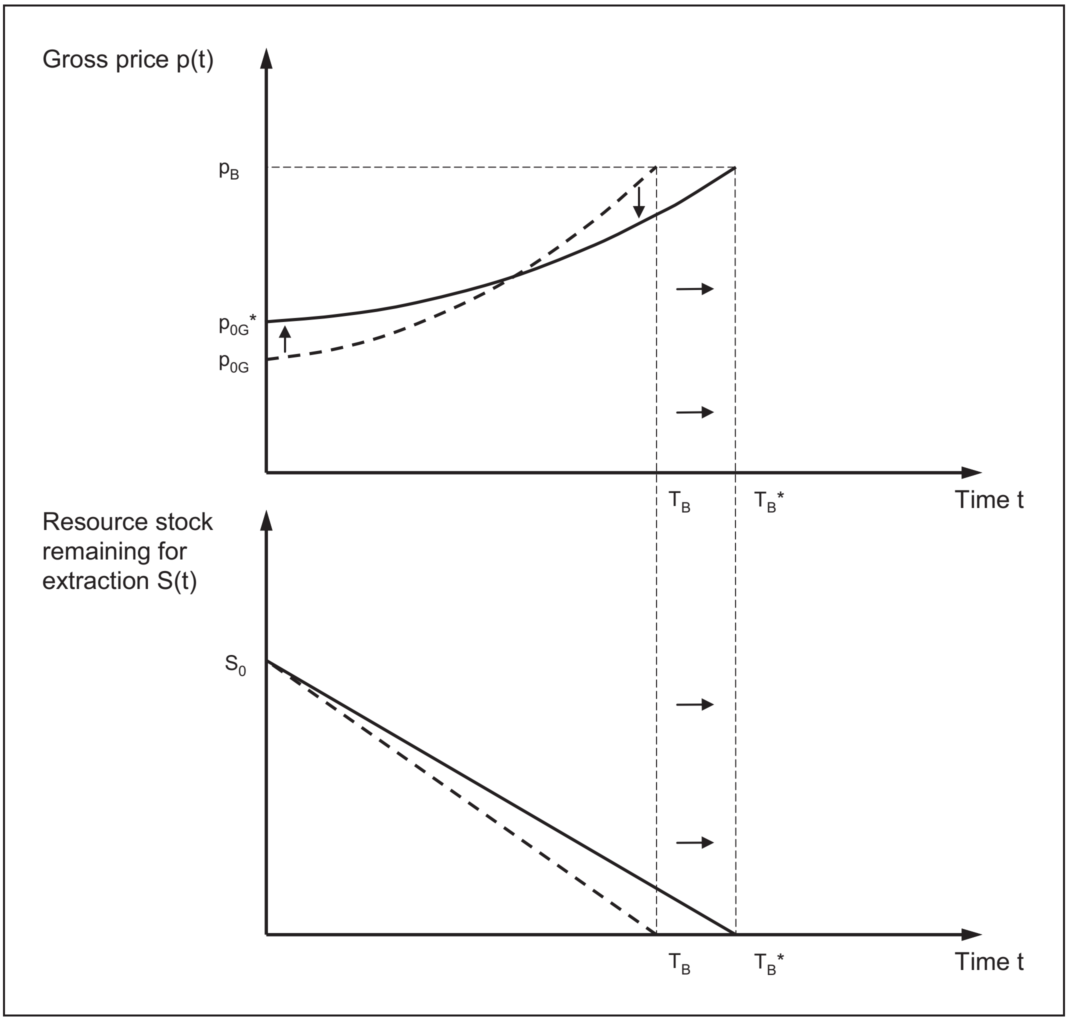
[32] For the sake of clarity, technological advance has not been discussed in the previous section about scarcity rent in order not to overload the topic.

Fig. 5-10 shows the impact of increasing marginal costs of production from c_R to c_R* on the gross price path over time. As Perman, Ma et al. (2003) demonstrate, this increase raises the initial gross price from p_{0G} to p_{0G}* while the growth rate of the gross price decreases. In addition, the time until complete exhaustion or until the price of a backstop technology p_B gets competitive is shifted from T_B to T_B*.



Source: Own representation based on Perman, Ma et al. (2003), p. 524

Fig. 5-10: Impact of increasing marginal costs of production on gross price

The rationale for this conclusion is as follows: Starting from the assumption that an increase in marginal production costs from c_R to c_R* would not impact the initial gross price p_{0G}

$$p_{0G}{}^* = p_{0G} \tag{5.2}$$

it follows that the new initial net price p_{0N}* is reduced:

$$p_{0N}{}^* = p_{0G}{}^* - c_R{}^* = p_{0G} - c_R{}^* < p_{0N} \tag{5.3}$$

The interest rate remaining unchanged, the new net price $p_N{}^*(t)$ would be lower than the initial net price path $p_N(t)$ at any point in time (cf. equation 5.1):

$$p_N{}^*(t) < p_N(t) \qquad \forall t \tag{5.4}$$

As marginal costs related to a higher production rate are simply added on top of the net price[33], also the new gross price path $p_G{}^*(t)$ would be lower than the initial price path at any time.

$$p_G{}^*(t) < p_G(t) \qquad \forall t \tag{5.5}$$

Assuming the absence of price elasticity effects, a continuously lower new gross price path would inevitably lead to higher demand in each period and consequently to a quicker depletion. The resource would be depleted before the unit price of the backstop technology is reached and the mine owner misses out on some of the possible profits. Furthermore, a continuously lower price path as a result of higher marginal costs of production seems counterintuitive.

It follows that equation (5.2) and consequentially also equation (5.5) cannot be valid. Instead, the new gross price $p_{0G}{}^*$ has to exceed p_{0G}:

$$p_{0G}{}^* > p_{0G} \tag{5.6}$$

Fig. 5-11 shows how the new price paths for net and gross price are set up. While the gross price rises from p_{0G} to $p_{0G}{}^*$, the net price falls from p_{0N} to $p_{0N}{}^*$. In other words, only a fraction of the cost increase can be passed on to the customer, the rest is borne by the mine owner. Due to its lower initial value, $p_N{}^*(t)$ rises slower than before. Equation (5.4) proves to be valid. The new gross price path $p_G{}^*(t)$ runs with a fixed markup of the new marginal costs of extraction $c_R{}^*$ above $p_N{}^*(t)$.

$$p_G{}^*(t) = p_N{}^*(t) + c_R{}^* \tag{5.7}$$

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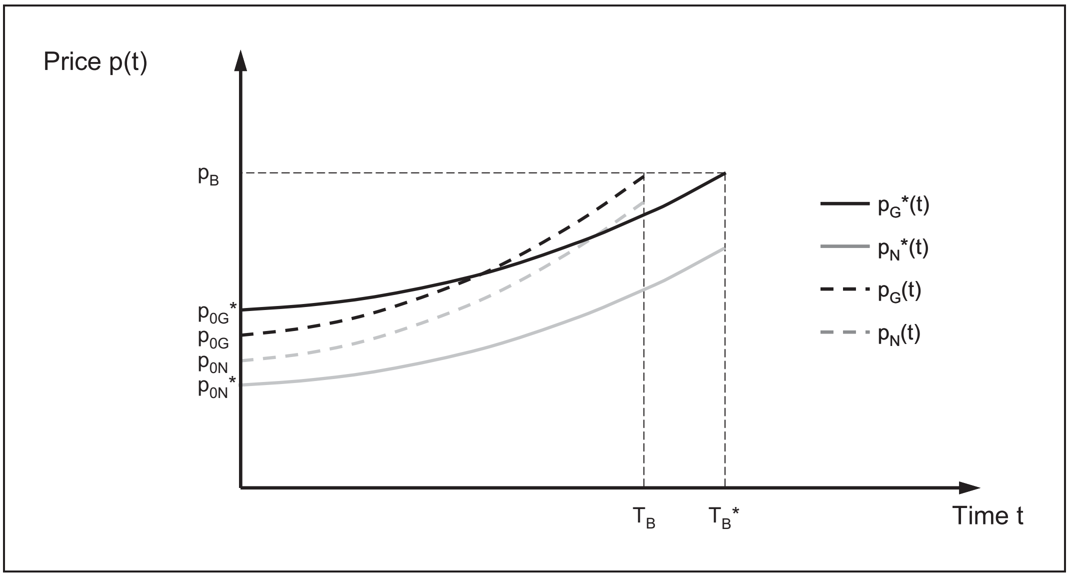
[33] For changes in marginal costs of production related to degree of depletion, refer to Fig. 5-9.



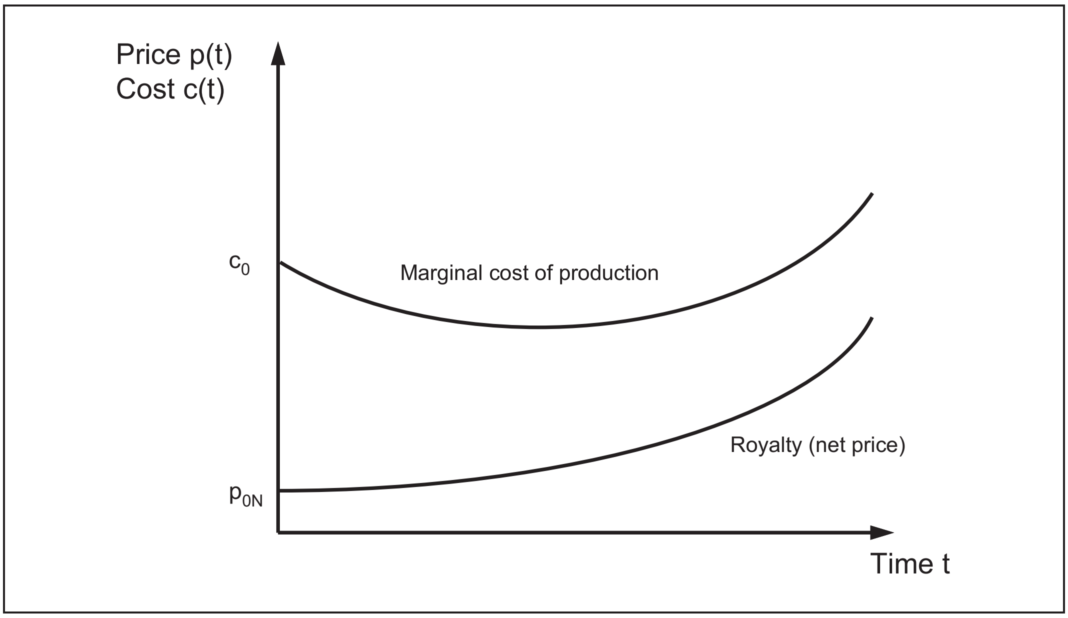
Source: Own representation based on
Perman, Ma et al. (2003), p. 523

Fig. 5-11: Impact of increasing marginal costs of production on gross and net prices

Based on that, $p_G^*(t)$ will intersect with $p_G(t)$ at some point in time, prolonging the time until the price of the backstop technology p_B is reached. Due to the higher gross price in the early phases of extraction, demand is initially lower. Therefore, the date of depletion is postponed. For decreasing marginal costs of production, i.e. $c_R^* < c_R$, the same effects in the opposite direction can be observed.

Adding up the three impacts on marginal production costs (rate of production, increasing depletion and technological advance), a U-shaped cost curve over time is to be expected (cf. Fig. 5-12). At the very beginning of the production of a fossil fuel, technology is still in its infancy and there are only few best practices and skilled workforce available. As technology advances and production knowledge cumulates over time, the production costs per unit start to decrease. In brief, the production cost curve of a specific fossil fuel shows the typical experience curve pattern at the beginning. Since the natural resource is perceived to be abundant initially, cost increases due to depletion effects are negligible. Though, as depletion becomes more important, a point will be reached where technological advance can no longer offset the higher operating expenses for resource extraction from smaller and less accessible deposits. Consequently, the marginal costs of production will stop the descent shown so far and will start to rise again. As discussed above, also scarcity rent will increase so that scarcity has a double price impact on resources nearing depletion.

The sum of the two price components in Fig. 5-12 (i.e. marginal cost of production and royalty) provides another explanation as to how observed market or gross prices can fall over time without violating the Hotelling rule (cf. subsection 5.1.1). At least in early phases of production, it is possible that the marginal costs of production decrease more rapidly than the royalty increases.



Source: Own representation based on
Pindyck (1978b) and Ströbele (1987), p. 45

Fig. 5-12: U-shaped curve of marginal costs of production

Another cost factor is the provision of spare production capacity which again is especially important in the oil industry. The OPEC countries in general and Saudi Arabia in particular have acted as swing producers over the last decades. This means that while the non-OPEC countries acted as price takers producing the amount of oil that was economically and technically viable for them at the given market price level, especially Saudi Arabia took the role of producing any additional volume required to satisfy the market demand. Saudi Arabia has been providing and still provides[34] spare production capacity in order to be able to respond quickly to sudden changes in supply and demand.

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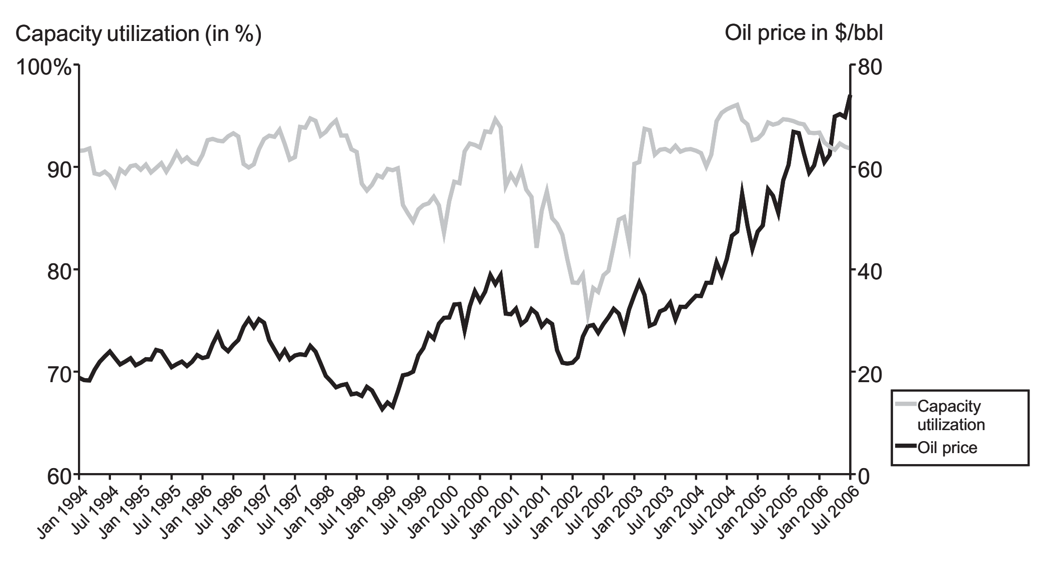
[34] Simmons (2005a) seriously doubts the current existence of significant excess production capacity in Saudi Arabia. "*By late 2004, the only apparent spare production capacity in the kingdom consisted of heavy oil*" (p. 188f).

For example, during the Iraqi invasion of Kuwait in 1990 which led to a complete shutdown of Kuwait's oil production and to an embargo of Iraq's oil exports, Saudi Arabia increased its production from 5.3 million bbl/d to over 8 million bbl/d within about three and a half months (cf. Simmons 2005a). This steep increase in production would not have been possible without the existence of under-utilized production facilities that could quickly be activated. The costs related to provide this spare capacity, i.e. construction and maintenance of non- or under-utilized facilities, are covered via a premium included in the market price of every barrel of oil.

This cost element is primarily relevant for crude oil production. For natural gas and coal the fluctuations in supply and demand volumes are not that significant as for oil. Therefore the provision of spare capacity can probably be neglected outside the oil industry.

Fig. 5-13 shows monthly data for OPEC capacity utilization and crude oil price. While the two time series are only poorly correlated to each other over the entire time span, there are certain periods in which there is a significant correlation between capacity utilization and price.



Source: Own representation based on OPEC (2007) and EIA/ DOE (2007)

Fig. 5-13: OPEC capacity utilization and oil price

For example, this can be observed from July 1999 until March 2002. During these 33 months, a substantial[35] correlation can be observed (cf. Fig. 5-14). Based on

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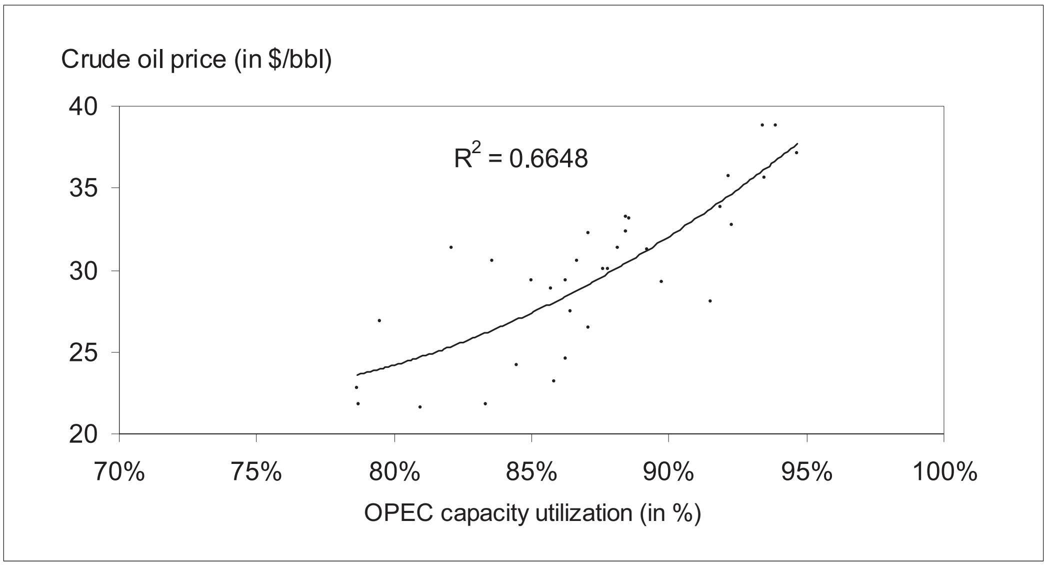
[35] Based on simple regression analysis. No econometric model formulated due to the autocorrelation of the coefficients.

that, it could be concluded that costs and thus price are influenced by OPEC capacity utilization in general, but that this effect is superposed by other key drivers.



Source: Own representation based on OPEC (2007) and EIA/ DOE (2007)

Fig. 5-14: Correlation between OPEC capacity utilization and oil price

Also relevant with regard to production capacities is the lead-time for the construction of new facilities[36]. In the conventional Hotelling approach, the time-to-build of capacities is not accounted for, since perfect foresight of the market participants is assumed. If this assumption is relaxed and market participants are allowed to be surprised e.g. by demand spikes or supply shortages of substitute goods, the unavailability of immediate capacity extension can lead to substantial price spikes.

One other uncertainty lies within the heterogeneity of a fossil fuel within one deposit on the one hand and across several deposits on the other hand. As discussed above, it is usually assumed that marginal costs of production gradually increase with depletion. This of course is only an expectation for the average extraction process.

The individual mine owner or the individual fossil fuel deposit can always be confronted with unexpected fluctuations of production costs in either direction, e.g.

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[36] Masseron (1990) distinguishes three categories of oil production capacity extensions: *Short-term capacities* are available within two years and require only small investments. *Medium-term* additions require about five years of lead-time and substantial investments. Extensions to reach the *maximum foreseeable capacity* take more than ten years with investments in the magnitude of several 10^{10} US-$ (cf. p. 74).

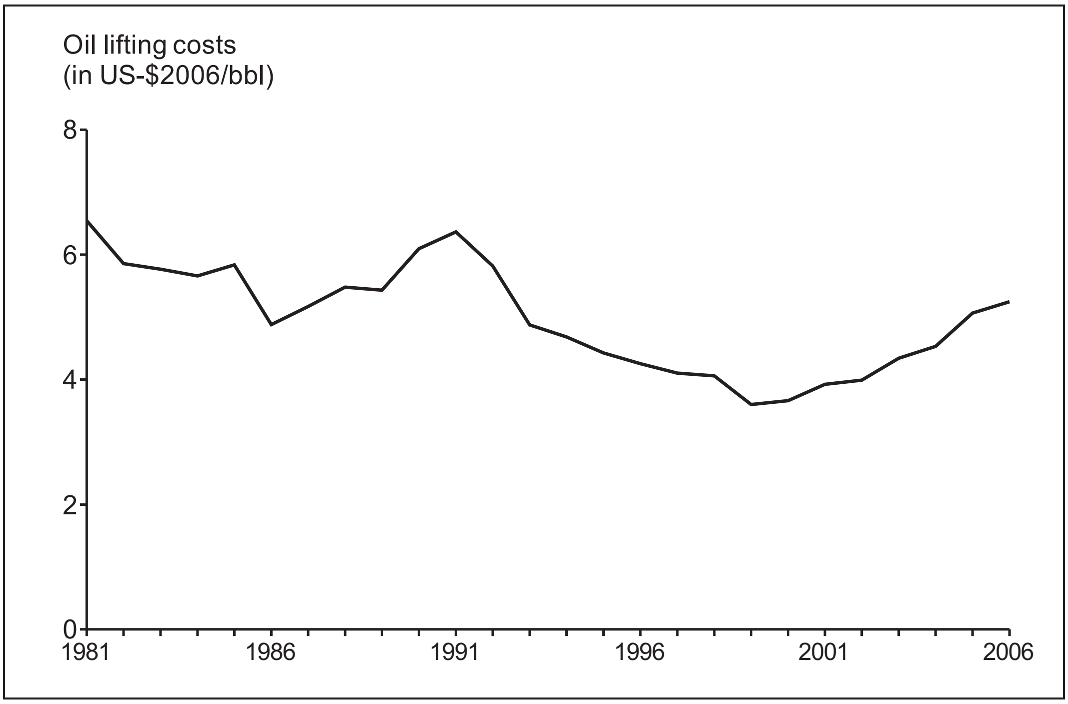
through unexpected changes of natural pressure in crude oil and natural gas reservoirs or unforeseen diameter changes of coal beds. Again, technology can help to reduce these uncertainties but can probably never completely eliminate them. When considering a mine owner with several deposits, it would be economically optimal for him to exploit the deposits with the lowest production costs first and then gradually move to the next-expensive deposit (cf. Dasgupta and Heal 1979, pp. 172ff., and Ströbele 1987, pp. 42f., for a detailed discussion). However, since the production costs of each deposit cannot be calculated ex-ante without uncertainty the mine owner can never be sure that he has chosen the right order of depletion.

While these two issues might pose a serious problem for the individual company, it can be doubted that this uncertainty has a significant impact on the formation of world market prices where individual miscalculations average out or are too small to make an impact. Therefore they will not be analyzed any further for the purpose of this thesis.

5.1.2.2 The opposite view: Continually decreasing production costs

As described above, both Adelman and Simon reject the validity of the "*law of diminishing returns*", as Simon (1996) calls it, i.e. the assumption that extraction costs inevitably rise over time due to ongoing depletion and the resort to smaller deposits with poorer quality. Both authors claim that ever since man started the extraction of resources, technological advance has been able to outpace increasing production costs. Simon (1996) argues that there is no convincing reason why this trend should come to an end, especially given the increased pace of technological development over the last decades: "*Is the rate of development of such new technologies slowing up? To the contrary: the pace of development of new technology seems to be increasing*" (Simon 1996, p. 30).

Adelman and Jacoby (1979) state that "*oil costs are everywhere only a small fraction of prevailing prices. Hence even substantial price changes would have little effect on supply*" (p. 35). Also the overview on oil production costs provided by Masseron (1990) shows cost data below 10 US-$/bbl, the only exception being marginal North Sea fields. As production costs over the last decades did not increase significantly (cf. Fig. 5-15), it could be concluded that (marginal) production costs are indeed not the key driver of fossil fuel prices.



Source: Own representation based on EIA/ DOE (2008)

Fig. 5-15: Oil lifting costs (outside U.S.)

If there were perfect competition, prices should indeed be close to marginal costs. But due to OPEC's cartel behavior and other political influences, "*the competitive thermostat has been disconnected*" (Adelman 2002, p. 171, also cf. Simon 1991b, p. 258). Therefore, Adelman and Jacoby (1979) discourage from using cost data for forecasting future price trends: "*A model driven by some assumed price-cost-profit equilibrium will probably not capture the essentials of the supply side of the market*" (p. 35).

Again, similar to the discussion of scarcity in subsection 5.1.1, a judgment which view on production costs is correct, cannot be easily made. In the end, only history can tell. For the time being, the long-term development of production costs remains one of the key uncertainties related to the fundamental analysis of fossil fuel prices. In the model developed in this thesis, this uncertainty can be reflected by the definition of different cases with different fuel availability. In each case, different fuel volumes are available at different production costs.

5.1.3 Cartel rent

Cartelization is primarily relevant for the price formation of crude oil, due to the high market share of the Organization of the Petroleum Exporting Countries

(OPEC)[37]. For natural gas and coal, a comparable organization of producers does not exist, at least not at the moment[38]. Consequently, the topics discussed here are currently only applicable to crude oil. Also, the effects of a monopolistic resource owner will not be discussed since this market structure is not relevant for fossil fuels[39].

The term *cartel rent* refers to the benefit that accrues to all producers due to the existence of a cartel in the market. Despite the expression cartel rent, gains related to the existence of a cartel in the market do not accrue to members of the cartel exclusively, but to all producing market participants. Since oil is traded at a common world market price[40], both the cartel and the fringe profit from higher prices due to cartel actions. Therefore, Dasgupta and Heal (1979) call fringe owners free-riders: "*They can afford to extol the virtues of free competition in public and frown on the activities of the cartel. In private they applaud the formation of the cartel*" (Dasgupta and Heal 1979, p. 349).

As Ströbele (1987) points out, the OPEC is not a cartel in a narrow sense. Despite defined production quotas, member states are free to exceed their production volume without any penalties. Also there is no common market information policy about production and reserves data. Ströbele therefore considers the OPEC rather as a cartel led by few dominating producers (i.e. Saudi Arabia, Kuwait and UAE) than a cartel with contractually fixed arrangements. Especially Saudi Arabia has been acting as price-setting swing producer. Other countries within and outside the OPEC adjust their production based on the price level set by Saudi Arabia. They are consequently called price-takers. The remaining demand is met by Saudi Arabia.

Also Adelman (1993) alludes to the fact that the OPEC is behind the scenes the arena for heated debates and intrigues between the member states. As each member country tries to maximize its benefits at the costs of other members, the existence of free production capacities serves as a lever for each member to improve its bargaining position. Free capacities can be used both as a threat to undercut supply restrictions as well as a tool to actually do so. Adelman cites Kuwait's oil minister who comments on the price decline in mid-1990 as follows:

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[37] Cf. e.g. Campbell (1997b), pp. 138 - 140, and Simmons (2005a), pp. 77 - 82, for a brief overview on OPEC's history.

[38] Nevertheless, recent news reported rumors about the upcoming formation of a "*gas OPEC*", likely to be led by Russia, Iran and Qatar (cf. e.g. Itar-Tass 2007).

[39] Cf. Dasgupta and Heal (1979), p. 323ff., and Perman, Ma et al. (2003), p. 518ff., for further details on monopolistic structures in resource extraction.

[40] Price differences between grades of crude oil are neglected for the purpose of simplification.

"*Those who could cheat, did. Those who couldn't, complained*" (Adelman 1993, p. 27).

Nevertheless, Adelman is convinced that the OPEC has a strong impact on market prices and thus is able to realize a cartel rent. For him, the oil crises in the 1970s were solely due to the exercise of market power and were completely unrelated to scarcity. He bases this perception on the observation that during the oil crises the high-cost producers (i.e. non-OPEC countries) increased their output as much as they could while the low-cost producers (i.e. OPEC members) reduced both output and investments, a clear sign for political influences in the market.

Adelman (1993) also refers to the price targets set by the OPEC. Around 1980, OPEC's long-term price policy committee set the target price in the range of costs for synthetic liquid fuels. "*That is a clear example of monopoly profit maximizing. For only when oil no longer competes with oil can its market price approach the supply price of the nearest alternatives*" (Adelman 1993, p. 17). Based on Adelman, the dependency on political decisions is the prime reason why crude oil shows such volatile price patterns[41].

Campbell (1997b), who usually disagrees with Adelman's viewpoint, admits that the OPEC in general and more specifically the market share of the swing producers[42] significantly impacts crude oil prices. In his opinion, the swing share exceeding 30 percent was a prerequisite for the 1970s oil crises.

Various approaches have been made to describe the OPEC's influence in a theoretical framework: Dasgupta and Heal (1979) describe the OPEC as a resource-owning cartel with a competitive fringe. Members of the competitive fringe are not able to influence the spot market price individually. They adjust their production to a level optimal at the price given by the cartel. The cartel sets the price of the natural resource in a way that the net present value of its profits is maximized (Stackelberg approach[43]). Assuming costless extraction and neglecting technical production limits, the existence of a competitive fringe results in a price path in compliance with the Hotelling rule (cf. equation 5.1): If the cartel would try to set

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[41] Not surprisingly, this view is also shared by Julian Simon. Cf. Simon (1991b), p. 258.

[42] Campbell (1997b) categorizes Abu Dhabi, Iran, Iraq, Kuwait and Saudi Arabia as well the Neutral Zone between Kuwait and Saudi Arabia as swing producers (cf. p. 97).

[43] Berg, Kverndokk et al. (1996) point out that there are several possible approaches to model the interrelations between the cartel and its fringe. The approach described above is a Stackelberg model with the cartel as market leader and the fringe reacting to the cartel's decisions. The cartel knows that and tries to anticipate the fringe's reaction when making its decision. Another popular approach is the *Nash-Cournot equilibrium* where both cartel and fringe consider the reaction of other players as given when deciding on their own strategy.

prices in a quasi-monopolistic way[44], all members of the fringe would immediately sell their entire stock and invest their proceeds at the market interest rate. This would lead to a temporary oversupply and a collapse of prices. Thus, as long as the stock of the competitive fringe is non-zero, it bars the cartel members from exercising monopolistic market powers.

A conceivable reaction from the cartel to end this constraint imposed by the fringe as quickly as possible would be to aim for very low prices in the beginning. The resulting increase in demand would rapidly deplete the fringe's deposits and put an end to the profit-limiting impact of the fringe. But due to the initial reduction in prices, also this strategy would lead to foregone profits in the short and medium term. Consequently, the Hotelling rule represents the optimal pricing strategy also for a market setup with a cartel and a competitive fringe.

Berg, Kverndokk et al. (1996) deny that the OPEC has enough market power to justify the approach by Dasgupta and Heal (1979) described above. They argue that the lack of coordinated actions does not add enough weight to OPEC's credibility in the market to dominate the strategy of the competitive fringe. In their view, each market participant decides independently on the optimal production strategy (Nash-Cournot approach).

A lot of analyses have been made to quantify the cartel rent. Three of them will be discussed here: a Stackelberg approach by Pindyck (1978a), a Nash-Cournot model by Berg, Kverndokk et al. (1996) and a correlation analysis by Erdmann (1995). Pindyck (1978a) uses a model based on the Stackelberg approach, with the OPEC acting as market leading cartel and the fringe adopting its actions to the OPEC's decisions. He concludes that the OPEC was able to realize a discounted cartel rent of 50 to 100 percent or even more compared to a market price under competition. These results prove to be relatively stable for significant variations of various assumptions made in the model (cf. Pindyck 1978a, p. 243).

In their approach based on a Nash-Cournot approach, Berg, Kverndokk et al. (1996) build two models to be able to quantify OPEC's cartel rent. While the first model describes the world oil market with a cartel and a competitive fringe, the second model represents a competitive market in which the OPEC countries only benefit from reduced costs of production but not from any cartel-related benefits. Based on this setup, they arrive at the conclusion that OPEC is able to realize

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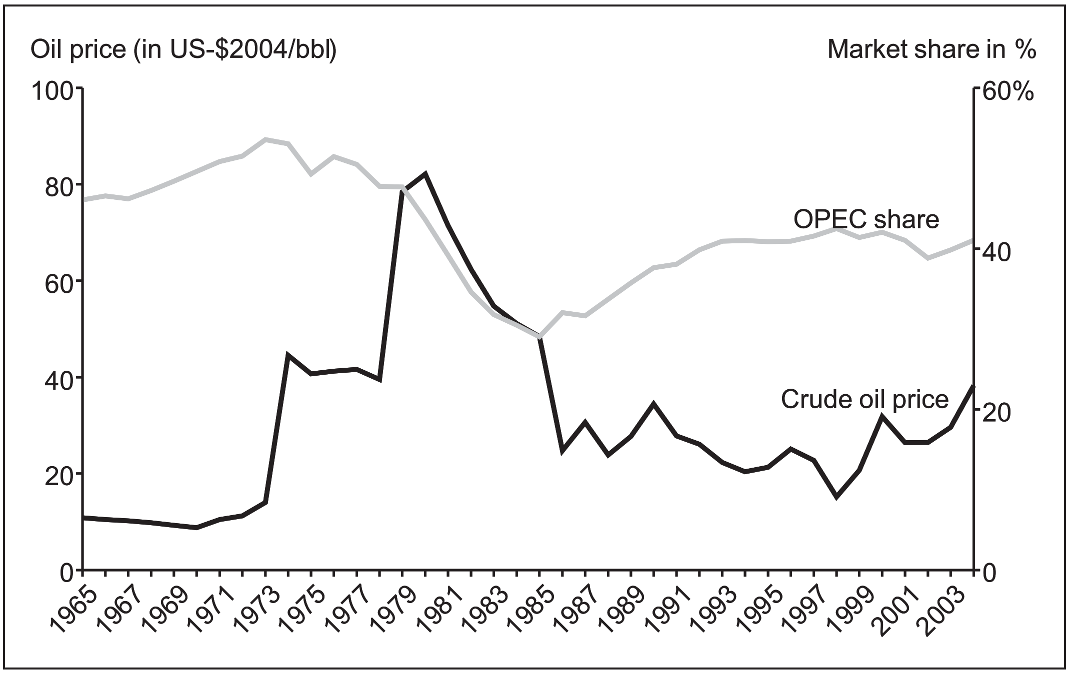
[44] Compared to perfectly competitive markets, resource extraction in a monopolistic market will lead to a higher initial net price with a lower rate of price increase. This leads to a lower demand at the beginning but a higher production rate at the end of the production period.

gains from cartelization in the magnitude of 17.5 percent in the long term. Looking ahead, they conclude that future gains from cartelization significantly depend on the reserves of the non-OPEC countries. Based on their results, an increase in the fringe's 1996 reserves of 25 percent would cut the cartel rent in half approximately. The rationale is that higher reserves stimulate the oil production of the fringe countries, reducing the OPEC's market share. Thus the price setting power and the ability to realize cartel rent is reduced.

Erdmann (1995) chooses a different approach to test historical data for the relation between crude oil prices and the OPEC's market share (cf. Fig. 5-16).



Source: Own representation based on
Erdmann (1995), p. 146,
updated with data from BP (2005)

Fig. 5-16: Crude oil prices and OPEC market share of world oil production

For an observation period from 1965 to 1991, he is able to verify a highly significant correlation between OPEC's world market share as dependent variable and the annual average of the crude oil price in the same year as well as the previous year's market share. An update of Erdmann's analysis with recent data shows that the correlation is still statistically significant[45]:

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[45] t-statistics shown in parentheses below coefficients. The application of t-statistics in this context is somewhat problematic due to the autocorrelation of the time series elements (cf. Poddig, Dichtl et al. 2003, p. 310ff.). Still, this methodology has been chosen here to allow the comparison to the original results of Erdmann (1995) where he chooses the same approach.

$$x_t = \underset{(t=2.740)}{4.404} - \underset{(t=-5.234)}{0.067}\, p_t + \underset{(t=26.333)}{0.943}\, x_{t-1} \tag{5.8}$$

t: *Period 1966 – 2004 (39 observations)*
x_t: *OPEC market share of world oil production in t (in %)*
p_t: *World market crude oil price in t (in US$$_{2004}$/bbl)*
Adj. R² *= 0.951*
Std. Error *= 1.484*

However, these updated results as well as Erdmann's original results should be treated with care. As the coefficient for p_t is very small (0.067 for the updated time series and 0.168 for Erdmann's analysis in 1995), it becomes clear that the high R^2-value is due to the fact that the market share is primarily correlated to the previous year's share and that the correlation with price can basically be neglected. Not permitting the previous year's share as explanatory variable, but focusing only on the correlation between market share and price, drastically reduces the adjusted R^2 to 0.04. In addition, the fact that a correlation exists, does not give any indication on the causality of events. In equation (5.8), the oil price p_t is an independent variable while the OPEC's market share x_t is the dependent variable. Assuming that the OPEC's ability to influence the oil price and to realize a cartel rent depends on the OPEC's market share, the econometric model should be specified the other way round, i.e. with the oil price as dependent variable.

Despite this poor correlation, there seems to be a connection between the OPEC's market share and the realization of a cartel rent. Taking into account the results from the first two studies mentioned above and considering the years used for the analyses, it becomes obvious that Pindyck (1978a), who uses data from years with an OPEC market share of temporarily above 50 percent, computes a much higher cartel rent than Berg, Kverndokk et al. (1996) who use data from years with market shares as low as 29 percent in 1985.

Going forward, the key uncertainty related to cartel rent is the development of the OPEC's market share. Given that the widely spread assumption is that the OPEC in general and the Middle East countries in particular will become increasingly important for the world's oil supply over the next decades, a rebound of the OPEC market share and thus a higher cartel rent might be expected. If and to what extent this will occur remains uncertain.

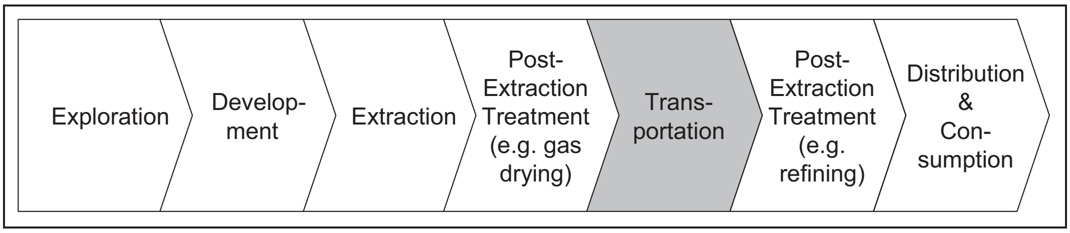
Still, the influence of the OPEC goes beyond the realization of a cartel rent. This can best be illustrated with Saudi Arabia's response to the eruption of the Yom Kippur War in the Middle East which then led to the first world oil crisis in 1973. Saudi Arabia announced a 10 percent cutback in oil production and laid an embargo on oil exports to the U.S.A. and the Netherlands. Other OPEC countries followed Saudi Arabia's example and cut their production by 5 percent. Although the reduction compared to world production was small, oil prices quadrupled from October 1973 until the end of the year (cf. e.g. Simmons 2005a). This effect does not describe what typically is referred to with the term cartel rent but it shows the impact of OPEC behavior on prices. The geopolitical influences on fossil fuels prices are discussed in more detail in subsection 5.3.2.

Another example can be found in recent OPEC statements regarding the increasing share of biofuels. The current secretary-general, Abdalla El-Badri, warns that OPEC countries might reduce their long-term investments in oil production capacities if Western countries continue to push the development of biofuels. He is quoted as saying that oil prices might go "*through the roof*" (quoted in Blas and Crooks 2007).

Based on the above findings, the explicit modeling of cartel rent appears difficult, given the ambiguous findings on the extent of the OPEC's influence. Especially a fundamental modeling approach complicates the use of game theory elements that would probably be most suitable to reflect the dynamic relationship between OPEC market share and oil price. Instead, a fixed multiple of production cost, based on the above estimations, might be used as a proxy in order not to completely neglect the impact of cartelization.

5.1.4 Transportation costs

Given that the focus of this thesis is on Europe, transportation is an important element of the supply chain (cf. Fig. 5-17) since a large part of the fossil fuels has to be imported. The two most relevant means of long-distance transportation are ocean shipment and pipelines.



Source: Own representation

Fig. 5-17: Transportation-related costs in fossil fuel production supply chain

90 percent of the international trade in oil and hard coal are carried out via ocean shipment. Also, 25 percent of internationally traded natural gas is transported via LNG tanker ships. In European territorial waters, the maritime trade volume of oil and gas accounts for 800 mill. t annually (cf. EU 2001). Pipeline transport is primarily relevant for gas imports from Russia and adjacent countries in the Caspian region.

Hatamian (1998) explains that transportation of natural gas, regardless whether by LNG tanker or by pipeline, will always be more expensive than the transportation of the equivalent amount of energy from hard coal or oil. This is due both to its lower energy density and to its gaseous form which adds to the technical requirements for the transportation infrastructure. For gas, transportation and distribution costs may account for up to 60 or 70 percent of the total cost incurred. Contrary to that, oil can be transported very easily and transportation costs are therefore almost negligible[46].

Transportation costs in a broader sense do not only include the regular freight rates charged by the shipping companies and pipeline operators but also the costs from environmental damages, e.g. from ship collisions, leaky pipelines or congestion of transit areas. To keep complexity at a manageable level, this type of transportation costs will not be further analyzed here. Instead, it is assumed that all external costs related to transportation will be covered by an insurance of which the premium is included in the freight rate.

With the exception of natural gas conveyed in pipelines, the oil price is a major price component for fossil fuels imported to Europe from overseas. Since all ships are fueled by fuel oils[47], an increase in crude oil prices will have a direct impact on shipping rates. Consequently, the future oil price development constitutes the major uncertainty of future transportation costs.

A second uncertainty with major impact on shipping rates is the availability of shipping capacity. As Rogers (2005) comments, there has been a capacity shortage until recently which drove up transportation rates. However, shipping companies are currently heavily investing in shipbuilding programs that will significantly alleviate that bottleneck within the next few years and might even lead to an

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[46] Following Hatamian (1998), the cost of transporting one natural gas unit of energy from the North Sea to Europe is equivalent to the cost of shipping the same amount of energy in oil two times around the world (p. 61).

[47] There are five types of maritime fuel oil, usually blends of gasoil and heavy fuel oil: marine gasoil (MGO), marine diesel oil (MDO), intermediate fuel oil (IFO), medium fuel oil (MFO) and heavy fuel oil (HFO).

overcapacity in the market, resulting in lower shipping rates (cf. Fromme and Berkenkopf 2004).

For the theoretical framework based on the Hotelling rule, the inclusion of transportation costs has the same impact as an increase in extraction costs. More specifically, transportation costs belong to the costs that increase with the rate of production.

5.2 Demand-side factors and uncertainties

Each discussion about price formation always has to take into account both supply and demand. In the first section of this chapter, demand patterns were assumed to be included ceteris paribus. This second section examines driving factors primarily on the demand side. Here, the main driver is the expected development of demand itself. An elaborated framework similar to the Hotelling rule does not exist. Thus, a descriptive and scenario-based approach is chosen: The first subsection 5.2.1 provides a general overview on global energy demand. The key demand sectors are introduced as well as some selected projections on the future of energy demand in Europe and on a global scale. In the further subsections, dedicated single aspects and uncertainties relevant for demand forecasts are discussed. Of course, all these aspects are or at least should be included in every demand projection in order to produce meaningful results.

5.2.1 General overview on energy demand

It is commonly accepted in the scientific community (cf. e.g. Hogan and Manne 1979, Nakicenovic, Gruebler et al. 1998, pp. 11ff., Deutscher Bundestag 2002, pp. 91ff., EU 2003a, p. 13, EIA/ DOE 2006, p. 11, and IEA 2006, pp. 55ff.) that economic growth, e.g. in terms of GDP growth, and population development are the two key indicators required to forecast energy demand. Nordhaus (1975) illustrates the difficulties of energy demand forecasts when he notes: "*estimating the demand for energy is conceptually difficult because energy is a derived demand rather than a final demand; that is, energy is demanded not for its own sake but because it can be combined with other inputs to produce satisfaction-yielding services*" (pp. 2f.). The underlying trends in population and GDP may be taken as included in the demand forecasts and therefore do not need to be discussed any further here.

Three well-established energy forecasts are chosen for further discussion at this point:

- World Energy, Technology and Climate Policy Outlook 2030 – WETO (EU 2003a)
- World Energy Outlook 2006 (IEA 2006)
- International Energy Outlook 2006 (EIA/ DOE 2006)

Tab. 5-1 and Tab. 5-2 below provide an overview on the setup and key assumptions as well as the results of the forecasts. Global final energy consumption is forecasted to grow at 1.6 to 2.0 percent annually. Key driver of this trend is Asia, while the shares of North America and Western Europe will decline. The study from EIA/ DOE (2006) shows the highest forecasts for energy demand, economic growth and efficiency gains. Final energy consumption in 2030 is forecasted to be 11 percent higher than in EU (2003a) and even 16 percent higher than in IEA (2006). Across the three publications, there is also a noticeable difference in the ratios of final energy consumption to primary energy production, probably due to differing definitions or methodologies[48].

All three forecasts predict the share of fossil fuels to maintain a level at or above 80 percent, which again emphasizes the relevance of this thesis also for coming decades. In general, the importance of coal and natural gas is assumed to increase at the expense of oil. Related to that, CO_2 emissions will grow at 1.7 to 2.1 percent annually in the Reference scenarios, questioning the realization of climate protection measures.

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[48] One possible explanation for these differences is a different treatment of non-commercial fuels, i.e. primarily with regard to the usage of fire wood in developing countries.

	EU 2003a	IEA 2006	EIA 2006
Title	**World Energy, Technology and Climate Policy Outlook 2030 – WETO**	**World Energy Outlook 2006**	**International Energy Outlook 2006**
Background	• Based on POLES model • Focus on Europe but in a global context	• Based on WEM model • IEA is part of the OECD • First published in 1993	• Based on SAGE model • Published by U.S. Dep. of Energy
Timespan covered	1990 - 2030	1990 - 2030	1980 - 2030
Assumptions for Reference scenario	• Continuation of ongoing trends • Benchmark for alternative scenarios	• Continuation of present policies • Starting point for further scenarios	• Impact of Kyoto Protocol not considered
Alternative scenarios and changed assumptions compared to Reference scenario	• Resources Low Case - Low oil & gas resources • Resources High Case - High gas resources • Technology Gas Case - Enhanced gas availability - Improved CCGT & fuel cell technologies • Technology Coal Case - Advanced solid fuel burning technologies • Technology Nuclear Case - Breakthrough in nuclear technology • Technology Renewables Case - Significantly improved renewable energies	• Alternative Policy Scenario - Adoption of all policies currently considered related to energy security and CO_2 emissions - Improved efficiency in energy production and use - Increased usage of non-fossil fuels - Sustainment of domestic supply of oil and gas as much as possible	• High Economic Growth Case - OECD economic growth +0.5%p - Non-OECD economic growth +1.0%p • Low Economic Growth Case - OECD economic growth -0.5%p - Non-OECD economic growth -1.0%p • Kyoto Protocol Case - CO_2 reduction targets assumed to remain valid until 2030 - Only Annex I countries reduce energy consumption; U.S., China and India do not

Source: Own representation based on EU (2003a), IEA (2006) and EIA/ DOE (2006)

Tab. 5-1: Energy demand forecasts: Qualitative overview

	EU 2003a				IEA 2006			EIA 2006			
	2000	2010	2020	2030	2004	2015	2030	2003	2010	2020	2030
World primary energy production [Mtoe]	9,953	12,110	14,611	17,213	11,204	14,071	17,095	10,505	12,728	15,307	18,019
World final energy consumption [Mtoe]	7,124	8,682	10,245	12,132	7,639	9,562	11,664	7,915	9,496	11,429	13,502
Share of fossil fuels[a]											
• **Total**	80%	83%	86%	87%	80%	78%	81%	86%	85%	86%	87%
• **Coal/ Lignite**	24%	24%	26%	28%	25%	25%	26%	24%	25%	26%	27%
• **Oil**	35%	35%	35%	34%	35%	32%	33%	39%	36%	34%	33%
• **Gas**	21%	24%	25%	25%	20%	21%	23%	23%	24%	25%	26%
Split by demand sector											
• **Resident. & Commerc.**	40%	39%	40%	42%	38%[d]	37%[d]	36%[d]	23%	24%	23%	22%
• **Industry**	36%	37%	37%	35%	33%[d]	34%[d]	34%[d]	50%	50%	54%	55%
• **Transportation**	24%	24%	23%	23%	26%[d]	27%[d]	27%[d]	27%	26%	23%	23%
Split by geogr. region											
• **Asia**	34%	38%	41%	43%	34%	37%	39%	29%	33%	35%	38%
• **North America**	24%	22%	19%	17%	25%	23%	21%	28%	26%	24%	23%
• **Western Europe**	16%	15%	13%	12%	17%	16%	14%	18%	17%	14%	13%
• **EEFSU**	11%	11%	11%	11%	9%	9%	8%	12%	11%	11%	11%
• **Africa**	8%	8%	9%	10%	6%	6%	6%	3%	3%	4%	4%
• **Latin America**	7%	7%	8%	8%	5%	5%	6%	5%	6%	6%	6%
• **Middle East**	b	b	b	b	4%	5%	6%	5%	5%	5%	5%
Increase p.a. until 2030											
• **World fin. energy cons.**	1.8%				1.6%			2.0%[e]			
• **Economic growth**	3.1%				3.4%			3.8%			
• **Population growth**	1.0%				1.0%			1.0%			
• **Energy density**[c]	-1.2%				-1.6%			-1.7%			
• **CO_2 emissions**	2.1%				1.7%			2.1%			

Source: Own representation based on
EU (2003a), IEA (2006) and EIA/ DOE (2006)

Tab. 5-2: Energy demand forecasts: Key results of Reference Scenarios

Note: Deviations of percentage sums from 100 percent due to rounding
a: Share of primary energy production
b: Middle East data included in Africa figures
c: Energy unit per GDP unit
d: Missing percentage points to 100 percent due to "*Non-energy use*"
e: Growth in primary energy production

5.2.2 Technological progress

Besides population and economic growth, technological progress is the third key demand driver that has not yet been mentioned. Generally speaking, technological progress can be divided into two categories: First, the improvement and further development of existing equipment and methodologies and second, the introduction of completely new, groundbreaking technologies. While the former case is a gradual, often unnoted process of our everyday life, the latter case is much more spectacular but also very rare. Pindyck (1980) emphasizes that "*the sudden invention and commercialization of a competitive substitute is rare; and it is more common to witness gradual changes in technologies, factor prices, other economic variables, and environmental restrictions that cause gradual changes (sometimes upward) in the costs of substitutes and thus gradual changes in resource demand. Random but continuous changes in demand over time lead to a different pattern of resource use than do discrete changes in demand*" (pp. 1205f.).

In the history of energy supply, there have been only few instances that can be classified as breakthrough technologies: the substitution of firewood through coal which then again was replaced by oil, power generation from nuclear fission and also the introduction of the industrial large-scale usage of renewable energy sources[49]. Also, it must be noted that gradual improvements are carried out on both the supply and demand sides of energy markets whereas the introduction of completely new technologies is primarily driven by the supply side and only in a second stage results in major changes on the demand side.

Within this thesis, this section dealing with technological progress has been assigned to the demand section of this chapter for two reasons: First, the breakthrough introduction of another fossil energy source as replacement for oil is very unlikely. It seems reasonable to assume that all possible natural resources have been examined and discarded hereon. Adding to that, the ongoing discussion about climate change measures makes a shift to non-fossil energy sources plausible, at least in the long run. As a result, the introduction of a non-fossil breakthrough technology will affect fossil fuels primarily on the demand side. Second, the effects of technological advancement on the supply side, i.e. on fuel availability and production costs, have already been discussed above and are implicitly included there.

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[49] Cf. section 5.1.1 for supply-related impacts of the introduction of a backstop technology.

In principle, the assessment of Simon (1996) about the extrapolation of past trends in fuel production costs into the future can be transferred to energy efficiency. If there are no immediate signs for a trend reversion, the optimal forecasting method is to extrapolate current trends into the future. As a matter of course, physical and technical constraints have to be considered, e.g. the three laws of thermodynamics for assumptions about efficiency rates. On a global scale, the assumption of continuously improving efficiency rates due to technological progress seems reasonable over the next decades, especially with regard to the significant share of low-efficiency facilities in the emerging countries that are likely to be upgraded or replaced over the next years and decades. Possible levers to assist this trend are the JI and CDM mechanisms of the Kyoto Protocol (cf. UNFCCC 1998, Articles 6 and 12, as well as subsection 5.2.4 of this thesis).

For modeling, Gately and Huntington (2002) call the application of a (constant) technology improvement rate "*autonomous energy efficiency improvement*" (p. 35). It needs to be kept in mind that the improvement is autonomous only in the model environment, i.e. it is not affected by prices, depletion or other factors. Obviously, this assumption does not pass a reality test.

Still, it can be concluded that gradual technological progress will definitely happen and only the degree of improvement is a source of uncertainty. In the absence of better data, extrapolation of past trends is likely to be a good proxy here.

When it comes to the introduction of new technologies due to major technological discoveries, forecasting becomes much more complicated. Dasgupta and Heal (1974) regard technology as the key uncertainty par excellence: "*It would seem plausible that the really important source of uncertainty is connected with future technology*" (p. 4). In their view, the uncertainty originates from the introduction date of a new technology rather than from its technical parameters. Consequently, they advise modelers to "*suppose that we know exactly the nature of the technical change that will occur, but we treat the date at which the event occurs as a random variable*" (Dasgupta and Heal 1974, p. 18). Adelman (1993) argues that the timing of a new technology is determined by its competitive position relative to existing technologies. A new technology will not be introduced as long as its costs exceed the costs of the incumbent technologies. For modeling, this means that the introduction can only be determined endogenously. Furthermore, as the technical specifications are currently unknown by definition, estimations have to be made, reducing the accuracy of the model: "*Nearly all the parameters* *must be invented out of thin air. Estimates are very sensitive to time factors and discount rates*" (Adelman 1993, p. 10).

To reflect the above discussion in an own model, the following approach seems advisable: To implement the uncertainty about future demand trends, different cases for final energy demand should be considered. Incremental technological advancement should be included as deterministic parameter, i.e. in slightly improving energy efficiency rates over time. In principle, the implementation as stochastic, i.e. varying, parameter would be possible as well. However, the additional insights gained from that are likely to be limited since different cases for the primary energy demand are already realized by the different cases for final energy demand.

5.2.3 Elasticities of demand and substitution effects

As Ströbele (1987) notices, demand for natural resources tends to be quite inelastic in the short and medium term. Especially for fossil fuels, this can be explained very easily: As opposed to fast moving consumer goods, fossil fuels cannot be substituted by other fuels in the short run. For example, a gas-fired power station cannot be converted to run with coal at all or only with major investments.

The effect of elastic demand reactions to changes in price or income can have various causes, often with the simultaneous occurrence of several effects. First, there is a change in total demand. For instance, when fuel prices start to rise, power producers will try to pass on the higher costs to their consumers. These end consumers will in turn try to cut down their electricity consumption, e.g. by using the air conditioning systems less frequently or only on a lower level. A similar example can be seen in individual motor car traffic where increasing gasoline prices might lead to a gradual reduction of average speed as well as reduced number and length of rides.

Second, fossil fuels can be substituted through capital, i.e. via a demand reduction through investments in more efficient technologies. For example, this can mean investments in more energy-efficient machinery or appliances at the end consumer level or in fuel-efficient car engines.

Third, a specific fossil fuel can be substituted with a different fossil fuel in the longer run, e.g. through the replacement of gas-fired power plants with coal-fired plants or vice versa.

All three alternatives have in common that the focus fully remains on fossil fuels. Only the total consumption level or the demand split over the fossil fuel types is adjusted to accommodate changes in price or income. Each of these alternatives will be discussed later. A fourth possibility is the substitution through non-fossil, e.g. nuclear or renewable energy sources. If the introduction of these new energy sources is predominantly a gradual process, the substitution with non-fossil fuels is similar to the substitution among fossil fuels. If a technology is introduced very quickly on a large scale, this is probably not a substitution process in the narrower sense but rather the introduction of a breakthrough technology as discussed in the previous section.

5.2.3.1 Changes in total demand: Price and income elasticities

In this section, two approaches of demand elasticity are discussed: price elasticity and income elasticity. Price elasticity of the demand describes the flexibility and the degree of reaction of the energy demand in response to price changes. Income elasticity describes the change in demand following a change in income or economic growth. Often, a distinction is made between short-term and long-term elasticity. However, there is no clear demarcation between short- and long-term in literature. For energy-related research, Atkins and Jazayeri (2004) point out that data is often available only on an annual basis. Thus, short-term elasticity is often measured on a yearly basis whereas long-term elasticity can cover periods from about three years up to several decades[50].

The price elasticity ε_{xp} of the demand is defined as (cf. e.g. Schumann 1992, p. 79, and Wöhe 1996, p. 666):

$$\varepsilon_{xp} = \frac{dx}{dp} \cdot \frac{p}{x} \tag{5.9}$$

with price $p > 0$ and demand $x > 0$. Since $\frac{dx}{dp}$ is usually negative, ε_{xp} is negative, too: When price increases, demand is reduced and vice versa. In the simplest case, price elasticity of the demand is constant, i.e. the coefficient has the same value regardless of the current price. However, it is also quite conceivable that the elasticity changes with the price.

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[50] In the context of power plant investments, *long-term* should be generally viewed in accordance with general economics as "*a time span sufficiently long so that all restrictions through existing capital stocks have vanished*" (cf. Weber 2005b, p. 231). The lifespan of a power plant usually is assumed to be 30 to 40 years (cf. Pfaffenberger and Hille 2004, p. 3.2, Weber and Swider 2004, p. 3 and Weber 2005b, p. 231).

There is a common agreement in the scientific community that for energy the long-term elasticity is significantly higher than the short-term elasticity. In other words, over several years, the demand for energy adapts to price changes whereas for periods of a year or less the lack in elasticity is one of the reasons why price spikes can occur: "*A sudden shock may create far more serious problems than the gradual long-run pressures of resource exhaustion*" (Hogan and Manne 1979, p. 9).

For their estimation of oil demand elasticity, Rehrl and Friedrich (2006), p. 2419, use the formula

$$\ln v(t) = c + \ln p(t) + \lambda \ln v(t-1) + \mu(t) \tag{5.10}$$

with
$v(t)$: crude oil demand in year t,
α: short-term price elasticity,
λ: parameter for time lag,
μ: error term

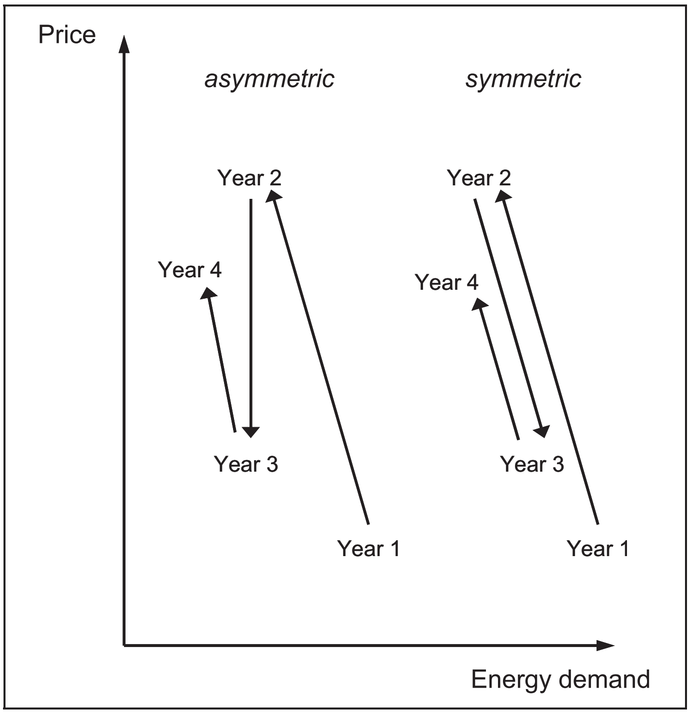
Using the transformation

$$\varepsilon_{xp} = \frac{\alpha}{1-\lambda} \tag{5.11}$$

the long-term elasticity ε_{xp} is computed to -0.458.

Accurate estimation is one of the key uncertainties related to elasticity: Hogan and Manne (1979) specify a range of -0.2 to -0.6 for long-term demand elasticity to primary energy prices. Manne (1979) calculates a long-term demand elasticity of -0.25 but emphasizes that any econometric estimation of the elasticity is highly prone to error: "*These econometric uncertainties would appear at least as great as the geological uncertainties on petroleum and uranium resources*" (Manne 1979, p. 212). According to Hogan and Manne, one likely source of error is the common assumption that investment patterns on the demand side remain unaffected by changes in energy availability, which is often made for simplification reasons. In their review of multiple studies on price elasticities for oil demand, Atkins and Jazayeri (2004) find ranges from -0.11 to 0.0 for the short term and from -0.64 to 0.0 for the long term. They find no proof that the demand elasticity differs significantly between developed and developing countries.

A second major uncertainty in estimating elasticity data is the assumption on symmetry or asymmetry. Atkins and Jazayeri (2004) reject the hypothesis of symmetric demand elasticity which is often made to uphold the linearity of a model. A symmetric elasticity of demand implies that the extent of demand change due to a price change is equal regardless whether prices increase or decrease. Atkins and Jazayeri maintain that a sudden price increase will induce patterns of demand reduction that will not be completely abandoned once prices return to their normal level (cf. Fig. 5-18). In addition, a second price shock does not necessarily create the same change in demand as the previous one. They call this phenomenon "*imperfect price reversibility*": "*The sign of the price shock is important.* […] *A large positive shock such as the 1970s may induce conservation. An ensuing negative shock may not then completely reverse the effects of the positive shock*" (Atkins and Jazayeri 2004, p. 9).



Source: Own representation based on
Gately and Huntington (2002), Fig. 2

Fig. 5-18: Symmetric and asymmetric price elasticity of demand

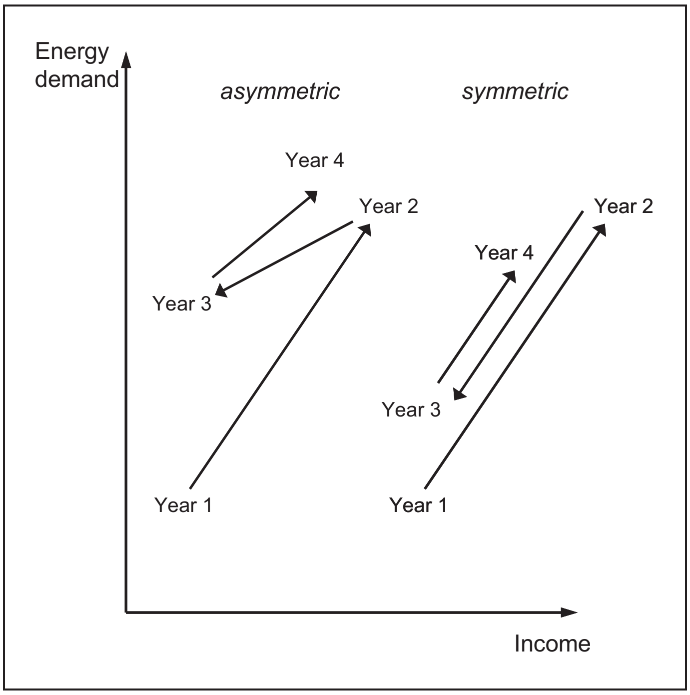
For modeling, the importance of the price elasticity of demand is often underestimated or left aside due to the above complications. In reviews of historical oil price forecasts in the past, Lynch (2002) and Bollen, Manders et al. (2004) conclude that one of the prime reasons for significant overestimations has been the negligence of elasticity of the demand. They advise a careful consideration of this parameter for future modeling. "*The over prediction of oil prices presented by many oil market analysts followed mainly from underestimation of the price elas-*

ticity of both the consumption of oil and the supply from non-OPEC countries" (Bollen, Manders et al. 2004, p. 48).

Income elasticity ε_{xe} of demand is defined as (cf. e.g. Schumann 1992, p. 81):

$$\varepsilon_{xe} = \frac{dx}{de} \cdot \frac{e}{x} \tag{5.12}$$

with income $e > 0$ and demand $x > 0$. Income elasticity ε_{xe} generally comes with a positive sign, i.e. growth in income and demand for energy are positively correlated. In principle, the points regarding time horizon and symmetry discussed for price elasticity are valid for income elasticity as well. The general difference between symmetric and asymmetric income elasticity is depicted in Fig. 5-19. Similar to price elasticity, demand-increasing income effects are likely not be completely offset by demand-reducing effects. Also, a second income increase does not necessarily lead to the same effect as a previous one.



Source: Own representation based on Gately and Huntington (2002), Fig. 2

Fig. 5-19: Symmetric and asymmetric income elasticity of demand

Nordhaus (1975) finds the income elasticity of energy demand to be relatively low, i.e. between 0 and 1. This means that the per capita energy demand tends to rise more slowly than income, assuming constant relative prices of energy compared to other goods. For net energy demand, Nordhaus calculates an income elasticity of 0.79 across 5 European countries and the U.S.A. Looking into each demand sector individually, the values differed quite significantly: Transportation had the highest elasticity (1.34), power generation the lowest (-0.05). Nordhaus explains the negative value with the transformation losses not related to income.

A comprehensive review of more recent income elasticity estimates can be found in Gately and Huntington (2002). In their own calculations, they find a range of 0.5 to 0.6 for OECD countries. For Non-OECD, they compute values of about 1 for countries with a continuously growing income and 0.5 for oil-importing countries with a slow and unsteady income growth. They advise strongly against using the same values for income and price elasticity since they find the speed in adjustment to changes in price to be slower than to changes in income.

Again, the key source of uncertainty for income elasticity is the estimation of the true parameter values. Gately and Huntington allude to the point that the specification of demand as function of income and price has significant impact on the values computed for the elasticities.

The distinction between price elasticity and income elasticity does not necessarily need to be modeled explicitly in a partial equilibrium model. Instead, only the short-term elasticity of demand can be implemented, based on an assessment of the above literature data sources. A value of -0.1 seems appropriate to reflect limited immediate responses to sudden price jumps. Long-term elasticity of the demand and substitution through capital (cf. subsection 5.2.3.2) does not need to be included in the model, because the application of different demand cases (cf. subsections 5.2.1 and 5.2.2) will lead to a similar effect. The substitution with other fossil fuels (cf. subsection 5.2.3.3) can be implicitly included in the model via the possibility to switch to a different fossil fuel. By confining the energy demand in the empiric model to the share covered by fossil fuels, also substitution with non-fossil fuels does not need to be included explicitly. Thus, substitution with non-fossil fuels can be assumed to be covered by both the short-term elasticity of the demand and different scenarios of final energy demand.

5.2.3.2 Substitution through capital

The substitution of non-renewable natural resources *R* by capital *K* describes the improvement of technology and process flows to use the resource more efficiently, i.e. to minimize the fuel input for a specific output or level of utility. Possible measures in the field of energy supply are a higher efficiency in the conversion of thermal energy into electric power, a reduction of losses in the transmission and distribution networks and more energy-efficient electric appliances. Each of these improvements requires capital investment and leads to a better utilization of the fuel input.

The degree of elasticity of substitution between energy and capital also determines the impact of scarcity on production. Hogan and Manne (1979) point out that a low level of possible substitution will lead to a significant effect of scarcity on the economy whereas better possibilities for substitution reduce the impact on the production level. As Perman, Ma et al. (2003) illustrate, a high elasticity allows the economy to replace a scarce resource by higher financial investments. This way, the scarcity becomes less significant, which results in a lower scarcity rent. If, on the other hand, a scarce resource can only be poorly substituted through capital, an impending scarcity will have more severe effects on scarcity rent.

Consequently, Perman, Ma et al. define the elasticity of substitution σ of a non-renewable resource through capital as "*the proportionate change in the ratio of capital to the resource in response to a proportionate change in the ratio of the marginal products of capital and the resource, conditional on total output Q remaining constant*" (Perman, Ma et al. 2003, p. 475):

$$\sigma = \frac{d(\frac{K}{R})}{\frac{K}{R}} / \frac{d(\frac{Q_K}{Q_R})}{\frac{Q_K}{Q_R}} = \frac{d(\frac{K}{R})}{\frac{K}{R}} \cdot \frac{\frac{Q_K}{Q_R}}{d(\frac{Q_K}{Q_R})} \tag{5.13}$$

with

Q = *constant,*

$Q_R = \frac{\partial Q}{\partial R}$: marginal product of the natural resource and

$Q_K = \frac{\partial Q}{\partial K}$: marginal product of capital.

In theory, the elasticity of the substitution can range from zero (i.e. no substitution possible at all) to infinity. An infinite elasticity of substitution means that capital and resource are perfect substitutes and are completely interchangeable. Obviously, neither upper nor lower bounds are realistic values for energy demand (cf. Hogan and Manne 1979, pp. 9f.). Of course, a certain degree of efficiency improvement, most likely with a diminishing marginal utility, can be realized through financial investment in power plant technology. However, a perfect substitution of fossil fuels through capital (as $\sigma=\infty$ would imply) will not be possible.

In addition to these considerations, Dasgupta and Heal (1979) show that for $\sigma>1$, the exhaustibility of a natural resource does not pose a significant threat for the long-term sustainability of the use of the input factor since it is not necessary for production. For $\sigma<1$, the natural resource is essential for the production and will be used up sooner or later. $\sigma=1$ describes the special case known as the *Cobb-Douglas Production Function*[51] (cf. equation 5.14).

$$Q = K^{\alpha_1} R^{\alpha_2} \tag{5.14}$$

with

$\alpha_1 + \alpha_2 = 1$
α_1: elasticity of output with respect to capital;
α_2: elasticity of output with respect to resource input.

In a Cobb-Douglas Production Function, the natural resource *R* is required for production. If $\alpha_2 \geq \alpha_1$, the natural resource is essential, i.e. a sustainable level of production with a perpetual substitution of the resource through capital is not possible. For $\alpha_2 < \alpha_1$, the natural resource is inessential and can be substituted. A sustainable level of production (i.e. consumption of the resource) is possible. Dasgupta and Heal conclude that, given the existence of a technology requiring an input pattern of the Cobb-Douglas type, "*exhaustible resources do not pose a fundamental problem if $\alpha_1 > \alpha_2$ which is presumably the best educated guess today*" (Dasgupta and Heal 1979, p. 205).

For empirical analyses, the elasticity of the substitution bears a significant element of uncertainty. As literature research (cf. e.g. Perman, Ma et al. 2003, pp. 478ff.) shows, even for historical data the identification of a reliable elasticity figure is very difficult due to poor data availability and noise problems. For forward-looking estimates, again technological advancement will be the key driver since it determines both technical feasibility and related costs. It is a moot point whether and to what degree historical data can be used to extrapolate future values: "*Even if we were to establish that substitutability had been high in the past, this does not imply that it will continue to be so in the future. It may be that as development pushes the economy to points where natural constraints begin to bite, substitution possibilities reduce significantly*" (Perman, Ma et al. 2003, p. 478).

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[51] Cf. Schumann (1992), p. 139ff, for a detailed discussion of the Cobb-Douglas Production Function

Hogan and Manne (1979) and Manne (1979) compute a value of $\sigma=0.25$ for the elasticity of substitution in the U.S. They show that the elasticity of substitution through capital is approximately equal to the absolute value of the price elasticity of demand for primary energy. However, they also admit that such a calculation always contains a substantial error margin and is therefore problematic. Despite its constraints and its age, this calculation is the only one discussed by Perman, Ma et al. (2003), nearly 25 years after the initial publication.

5.2.3.3 Substitution through other fossil fuels

For the calculation of the elasticity of substitution through other fossil fuels, both the theoretical background and the underlying uncertainties are the same as described in the previous section, with the only difference that now two natural resources R_1 and R_2 are used instead of one natural resource R and capital K.

One of the key differences compared to substitution through capital investment is that the elasticity for substitution through a different fossil fuel is likely to differ more widely between the various demand sectors. It can be argued that the elasticity of substitution in the transportation sector with its high dependency on oil products is lower than in other sectors where fuels can be switched more easily, e.g. in heating.

Hatamian (1998) distinguishes between demand for *specialized* and *bulk* fuels. Specialized fuels are required for a certain purpose due to technical requirements and can hardly be substituted. Again, prominent example is the usage of oil products in the transportation sector. Contrary to that, bulk fuels have the primary purpose of providing light or heat or are transformed into electricity, e.g. coal. Hatamian regards bulk fuels as the sector in which interfuel substitution is most likely to happen. Key decision parameters are not only fuel costs but also e.g. capital and operative expenditures, CO_2 emission and other environmental costs as well as security of supply. Depending on the future development of the CO_2 emission certificate prices, CO_2-intensive fuels (i.e. hard coal and lignite) are likely to be substituted by less CO_2-intensive fuels, primarily natural gas. A detailed discussion of CO_2 emission cost can be found in section 5.2.4.

Related to the discussion about substitution among fossil fuels is the indexation of natural gas prices to crude oil prices. Especially for Europe, natural gas has been usually traded under long-term contracts, so-called *take-or-pay* agreements. In these types of contracts, the seller agrees to provide a defined volume of natural gas per year. The buying party is committed to receive that volume or to pay for the gas, even if not physically accepted. The volume being contractually fixed, the gas price is linked to the oil price. This leaves the buyer with the volume risk and the supplier with the price risk.

Historically, the oil-price indexation of gas has two major reasons. First, natural gas was considered as a by-product of oil production with no or only low intrinsic market value. Oil prices were used as a benchmark to deduct meaningful market prices for gas. Second, since the majority of gas supply contracts has been based on long-term agreements, the market for natural gas has not been liquid enough to allow for the formation of true market prices based on available supply and demand. Hence natural gas prices have been linked to prices for relevant substitute primary fuels, i.e. most notably crude oil. The indexation equation allows gas prices to follow the fluctuations of the oil prices, but keeps them low enough to prevent any incentive for gas users to switch to oil (cf. Siliverstovs, Neumann et al. 2004, p. 3).

The worldwide trend towards liberalization of energy markets leads to a decreasing relevance of long-term contracts. For Europe, Neumann and Hirschhausen (2004) show a significant decrease in the length of take-or-pay contracts over the last 20 years. Even though they can not prove a direct correlation between contract length and importance of oil-price indexation, they argue that market liberalization has the effects that "*contract lengths are shrinking, oil-price indexation is diminishing in importance, and flexibility in the terms of the contract (take-or-pay obligations and swing) is increasing*" (Neumann and Hirschhausen 2004, p. 175).

Even if a strict indexation of oil and gas prices will be abandoned at some point in the future, the development of both prices is very likely to remain closely interrelated due to their high degree of substitutability both for thermal and non-thermal applications. Given its broad range of application and its undisputed importance for the global economy, crude oil is at the top of a primary fuel price hierarchy. As such, oil price movements would still be reflected in the prices of natural gas or other primary fuels. Gordon (2005) writes: "*The logical order* […] *is from oil to gas to coal to consumption. Oil developments determine the profitability of massive ocean transport of natural gas. Similarly, extensive expansion of coal use will occur only if oil and gas become sufficiently expensive*" (p. 129).

5.2.4 Costs and opportunity costs of greenhouse gas emissions

It goes without saying that there cannot be a discussion of the future of fossil fuels without considering climate change. Global warming has become an omnipresent topic, both in the scientific community as well as in the general public. Even at the G8 conference in 2007, climate change was one of the most prominent focal points of discussions (cf. e.g. Vorholz 2007). The latest scientific results can be found in the publications of the IPCC (cf. e.g. IPCC 2007a, 2007b, 2007c).

This subsection provides a brief overview on the current measures to reduce greenhouse gas emissions, primarily focusing on the Kyoto Protocol (cf. e.g. IEA 2002 for a comprehensive overview on climate change policies). Since the validity period of the protocol expires after 2012, also the so-called *Post-Kyoto period* is discussed, which represents the key economic uncertainty in the context of greenhouse gas emission costs.

The history of political efforts to mitigate climate change started in 1979 with the First World Climate Conference. Since then, many international climate conferences have been held (cf. UNFCCC 2005, p. 5, for a timeline of conventions), e.g. the 12th Conference of the Parties, held at Nairobi in November 2006 (cf. UNFCCC 2007a, 2007b) and the 13th Conference of the Parties in Bali in December 2007 (cf. UNFCCC 2008a, 2008b). In February 2005, the Kyoto Protocol (cf. UNFCCC 1998) entered into force. It postulates targets for emission reduction of six greenhouse gases[52] for the period from 2008 until 2012. During this period, greenhouse gas emissions of industrialized countries should be reduced by five percent compared to the 1990 emission volume. As of April 2008, 179 countries had ratified the protocol. The U.S.A., one of the largest emitters of greenhouse gases, is probably the most prominent country that has not ratified the Kyoto Protocol yet (as of April 2008, cf. UNFCCC 2008c)

In the Kyoto Protocol, countries are classified into three groups: The group of *Annex I countries* is comprised of industrialized countries that were members of the OECD in 1992 plus various countries labeled as *economies in transition*[53]. *Annex II* refers to the OECD member countries only. In the group of *Non-Annex I countries* are predominantly developing countries[54]. It is important to note that the declared targets for emission reduction apply only for the Annex I countries (cf. Art. 3 of the Kyoto protocol).

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[52] Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydro fluoro compounds (HFCs) and perfluorocarbon compounds (PFCs)

[53] The current list of Annex I countries can be found at *http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php* (accessed June 25, 2007).

[54] The current list of Non-Annex I countries can be found at *http://unfccc.int/parties_and_observers/parties/non_annex_i/items/2833.php* (accessed June 25, 2007).

The Kyoto Protocol lists three instruments for emission reduction explicitly, i.e. Joint Implementation (JI, Art. 6), Clean Development Mechanism (CDM, Art. 12) and Emissions Trading (ET, Art. 17), cf. UNFCCC (2005):

- The *Joint Implementation* mechanism provides guidelines for the cooperation of two Annex I countries. If the activities of one Annex I country lead to the installment of emission-reducing technologies in a second Annex I country, the first country is credited with Emission Reduction Units (ERU), i.e. additional emission certificates. For the second country where the reduction measures have been realized, the emission allowance is reduced accordingly. It follows that JI measures do not impact the global emission cap but only the allocation of emission allowances among the Annex I countries.

- Very similar to JI is the *Clean Development Mechanism*. The key difference is that an Annex I country realizes a project for emission reduction in a Non-Annex I country and is credited with Certified Emission Reductions (CER) in return, i.e. another type of additional emission certificates. Since Non-Annex I countries do not have reduction targets or emission limits of their own, the implementation of a CDM measure can result in a lower reduction of the global emissions. To mitigate this effect, CERs are limited to one percent of the respective Annex I country's emission allowance per year. Some other restrictions apply, e.g. the exclusion of reductions through nuclear technologies as well as the requirement that reductions need to be realized that would otherwise not have been implemented.

- The third instrument provided by the Kyoto Protocol is *Emissions Trading*. Based on the requirement that all greenhouse gas emissions need to be covered by emission rights or certificates, Annex I countries are allowed to trade the emission rights based on their initial emission allowances (Assigned Amount Units – AAUs) as well as ERUs and CERs. This way, each Annex I country can choose whether it is cheaper to install additional emission reduction technologies or to purchase emission rights from other Annex I countries with lower emission abatement costs. Thus, the price of emission certificates should equal the marginal emission abatement costs. In the EU, the emissions trading scheme ETS has been in place since 2005 to allow parties from all EU countries to trade their CO_2 emission rights (cf. EU 2005c).

All these measures are open not only to countries but also to private entities, thus enabling companies to participate in an emissions trading scheme or to realize JI and CDM measures. Currently, the reduction targets per countries are broken down by industry and by company in *Nation Allocation Plans* (NAPs)[55]. Thereby, all economic entities in industries currently included in the Kyoto Protocol reduction targets are directly affected by emission caps and costs.

Among others, Böhringer and Vogt (2001) heavily criticize the achievements of the Kyoto Protocol and state that such an agreement could only be reached by disregarding some major aspects. One of their key points which they call *climate dilemma* is due to climate protection being a public good and the related free-rider problem: Public goods are characterized by the fact that nobody can be excluded from their usage, whether he is paying for the good or not (cf. e.g. Schumann 1992, p. 41). In the case of climate protection, this means that countries may benefit from the attempts of other countries without occurring any costs or constraints: "*Everybody could be better off through cooperation, but there is no incentive for a single country to act cooperatively*" (Böhringer and Vogt 2001, p. 3). All cooperation between autonomous countries occurs on a voluntary basis, there is no instrument or authority that can enforce cooperation. From the viewpoint of a single country, the optimal strategy regarding climate protection is always faineance. If all other countries significantly invest in emission reduction technologies, a free-riding country will benefit from the reduction of global warming without any costs or limitations for its economy. If no other country invests in climate protection measures, the contribution of a single country would be worthless since the impact on global warming is too small. The importance of this point is highlighted by the fact that the U.S.A. have not ratified the Kyoto Protocol yet.

However, all these regulations and points of criticism are primarily related to the period until 2012. Whatever comes beyond that date is highly uncertain since no agreements have been found yet. In theory, the long-term results of global climate change policies could range from a complete turning away from climate protection measures due to high costs and increasing competition (cf. the discussion of the climate dilemma above) to the introduction of a global emission trading scheme. The array of uncertainties related to greenhouse gas emission costs and thus to the future competitiveness of fossil fuels is thus multidimensional:

- Will there be emission volume restrictions after 2012 and to what extent?

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[55] Cf. EU (2005c), p. 11, for the implementation of NAPs in the European emission trading scheme. Also cf. BMU (2006) for the German NAP for the period 2008 – 2012.

- Will the restrictions apply globally or only for some regions in the world? In particular, will large greenhouse gas emitters like the U.S.A., China or India actively participate in climate protection efforts and how does that affect the efforts of other countries?
- Will other energy demand sectors that are currently excluded from reduction targets, e.g. transportation, be included into reduction schemes as well?

From an economic point of view, it all can be aggregated into one question: How will the costs for emission certificates or marginal emission abatement costs develop over time? Low emission (opportunity) costs will favor technologies using fossil fuels with a high CO_2 intensity (e.g. lignite in power generation), high emission costs will promote the usage of fuels with low CO_2 intensity (e.g. natural gas) or the development of carbon capture and sequestration technologies (CCS).

Of course, many proposals have been made regarding climate protection measures and emission caps after 2012. Clearly, it goes far beyond the scope of this thesis to present and discuss them in detail. Four approaches shall be briefly presented here, primarily to illustrate the broadness and variety of the proposals, creating the vast uncertainties related to emission costs.

First, based on the assumption that emission abatement costs are likely to rise faster than the realized benefits from climate change mitigation, the IEA propose the introduction of two alternative mechanisms to manage emission volumes (cf. IEA 2002, 2003): *emission right price caps* for industrialized countries in combination with non-binding targets for developing countries on the one hand or *dynamic target setting* on the other hand. The first tool, emission right price caps, is meant to limit the maximum prices for traded emission certificates in industrialized countries by issuing an unlimited number of additional certificates at a defined price, set in the upper range of expected emission abatement costs. Revenues generated from the additional sales could be used to promote further R&D activities related to climate protection or to implement additional CDM measures. This approach is based on the perception that "*higher-than-expected abatement costs fully justify higher emission paths and eventually higher stabilisation levels*" (IEA 2003, p. 8), a view likely to be contested by other parties engaged in climate protection. In addition, non-binding emission targets are set for developing countries which can be regarded as a variation of the above price cap approach with prices for additional certificates set to zero. To prevent a transfer of these free emission rights to industrialized countries, global certificate trading must be limited, e.g. by only allowing countries which have met their non-binding targets to sell their excess permits. Thereby, an incentive for developing countries to adhere to their emission cap could be generated.

The other IEA proposal, dynamic target setting, is based on the definition of flexible emission caps for each country, e.g. based on the development of certain economic and social indices like GDP or population. This approach would eliminate the uncertainty related to future economic development, thus reducing the abatement cost uncertainties induced by a fixed emission cap with uncertain economic growth.

Second, the European Committee of the Regions calls for reduction targets for developed countries in the magnitude of 15 to 30 percent in 2020 and of 60 to 80 percent in 2050, taking again the 1990 values from the Kyoto Protocol as benchmark (cf. EU 2005b, p. 4). However, the tools to achieve these reductions are not specified.

Third, the non-government organization CAN (Climate Action Network), a consortium of over 365 individual NGOs (cf. CAN 2007), proposes a three-track approach (cf. Morgan 2004). It is aimed at keeping the global warming below 2°C but does not translate that into dedicated emission reduction targets. The first track, called *Kyoto Track*, is targeted at continuing the mechanisms of the Kyoto Protocol, mandatory for industrialized countries. It is meant to drive the development and installation of clean technologies. In the second track, the *Greening* or *Decarbonisation Track*, developing countries shall benefit from a technology transfer from the industrialized countries, thus enabling a low profile carbon footprint of the developing countries. The third track, called *Adaptation*, is meant to specifically help countries that are most exposed to unavoidable effects of the global warming. Industrialized countries shall be required to help these countries adapting to climate change effects, also paying compensation, if required.

A fourth approach is taken by the Asia-Pacific Partnership on Clean Development and Climate (APP), consisting of Australia, China, India, Japan, the Republic of Korea, and the U.S.A. Following their Vision Statement, they want to fight global warming by intensifying research on new technologies, primarily in the fields of "*energy efficiency, clean coal, integrated gasification combined cycle, liquefied natural gas, carbon capture and storage, combined heat and power, methane capture and use, civilian nuclear power, geothermal, rural/ village energy systems, advanced transportation, building and home construction and operation, bioenergy, agriculture and forestry, hydropower, wind power, solar power, and* *other renewables*" (U.S. Department of State 2005). The partnership is meant to foster experience sharing and yield better results through joint research. It is emphasized that the efforts of the APP are in addition to and do not compete with the Kyoto Protocol. Still, the approach is very different to the Kyoto Protocol: Instead of defining reduction targets and a regulatory framework and then letting the market figure out the most efficient technologies (*market pull*, cf. Donner and Stratmann 2005, p. 4), the APP approach focuses on the promotion of selected technologies while avoiding defined reduction targets (*technology push*).

For each of these approaches, the long-term effects on CO_2 emission or abatement costs are very hard or even impossible to quantify. For the purposes of this thesis, again the application of different stochastic cases seems appropriate to reflect these uncertainties.

5.2.5 Guaranteed satisfaction of demand and diversification of fuels

Guaranteed demand satisfaction is always an issue if there is a strong dependency on one or several natural resources that cannot be substituted easily, at least not on short notice. Ströbele (1987) emphasizes that the economic damage, i.e. the costs of unavailability of a natural resource, can exceed the value of the resource many times over. The European Union[56] is currently importing about 50 percent of its primary fuel consumption (cf. Fig. 5-20) and thus has a substantial interest in a secure and diversified supply.

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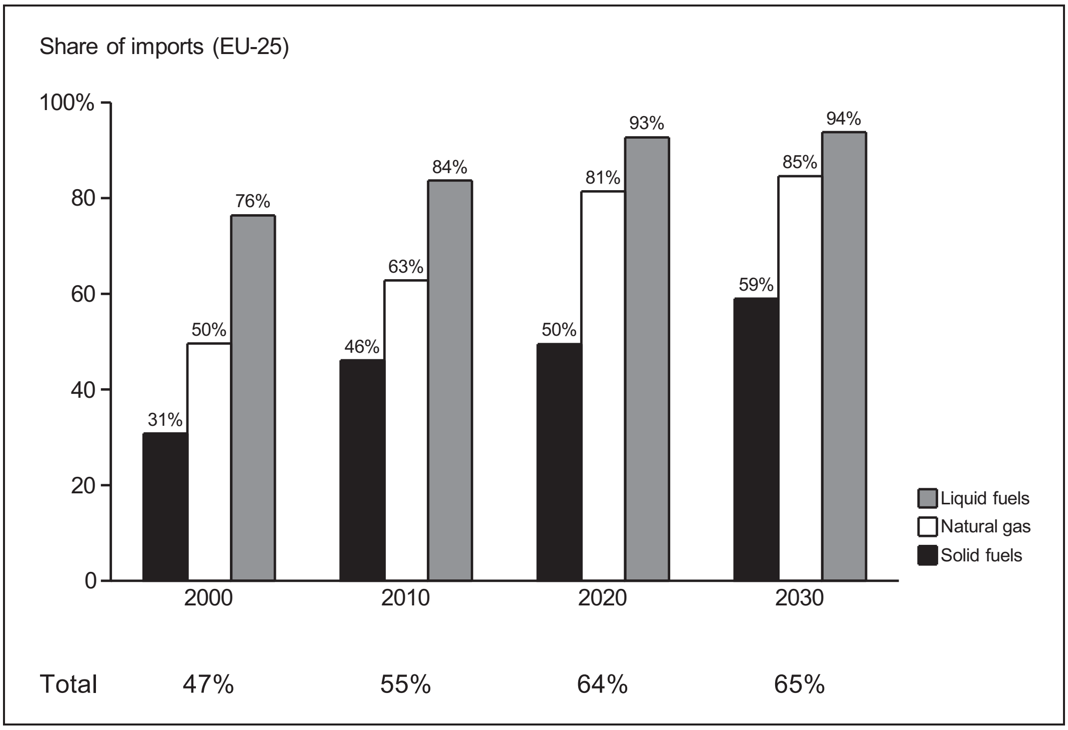
[56] On the demand side, Western Europe is the primary scope of this thesis. Thus, the discussion of secure supply focuses on Europe in general and on the EU in particular. Nonetheless, security of supply is also important for other regions, e.g. for North America.

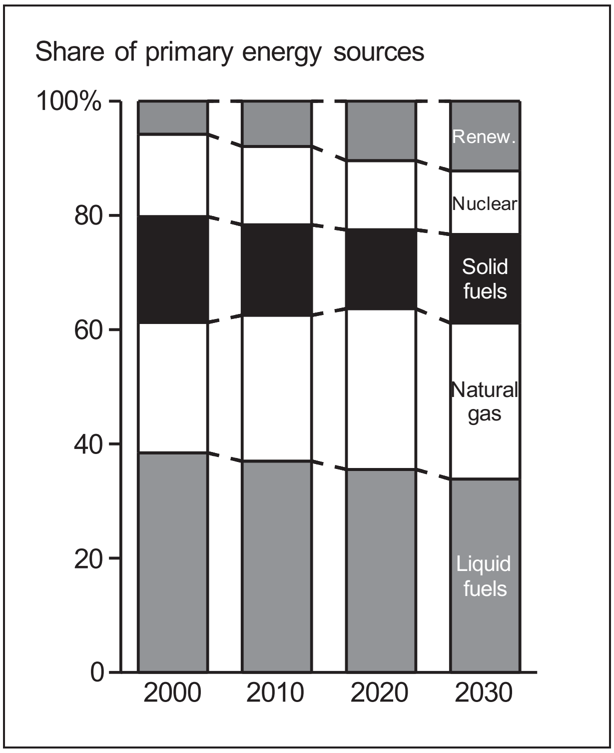


Source: Own representation based on EU (2006), p. 26

Fig. 5-20: EU primary fuel demand – share of imports

Guaranteed demand satisfaction was already one of the key motives for the foundation of the European Coal and Steel Community, the predecessor of the European Union, back in 1951. Diversification as one key measure to improve the security of supply and thus guaranteed demand satisfaction can be seen on two dimensions: supplying regions and types of fuel. For the former category, the global endowment with natural resources must be taken as a given and limits the possibilities for optimization from a European perspective:

"*Alternative supplies from Russia and Africa could offer some degree of diversification of oil supplies, but cannot compensate for a substantial disruption originating in the Persian Gulf.* […] *The dependence of the EU on large volumes of imported pipeline gas from Russia and Algeria creates a high level of structural dependence.* […] *A growing capacity to receive gas in the form of Liquefied Natural Gas (LNG) allows for some diversification, but to quickly shift supplies from the two main suppliers to LNG is hardly feasible*" (CIEP 2004, p. 21). Regarding the diversification of fuels, Europe has successfully reduced its dependence on crude oil from about 60 percent in the 1970s to some 40 percent today. This trend is forecasted to continue over the next decades (cf. Fig. 5-21).



Source: Own representation based on EU (2006), p. 26

Fig. 5-21: EU primary fuel demand – share of fuel types

It is important to note that the European measures for a sustainable energy supply will only have a limited effect on world market prices. The EU can hardly control any of the main key drivers of world fuel prices: All major suppliers are located outside the EU, the regions with the highest demand growth are non-European and also the prevailing sources of geopolitical risks and uncertainties are beyond European reach. Due to the significance of secure supply for the European perspective, the situation and countermeasures are introduced here all identical.

In the European Green Paper (EU 2001), the political target of secure energy supply is defined as the sustained provision of energy at affordable prices, also considering environmental constraints and sustainable development. It is made clear that the EU does neither strive for autarky nor for the lowest level of imports possible, but aims at reducing the risks connected to the dependency of imports.

As laid out, the focus of the European activities is on the demand side. A package of measures is defined in EU (2001) to mitigate possible negative effects of the import dependency:

- *Strategic partnering with major supplier and transit countries*: This measure is primarily focused at Russia and the countries at the Caspian Sea region due to their relevance for the European natural gas supply. Also transit countries, i.e. countries the pipelines have to cross, are included. The idea is to maintain permanent good relationships in order to avoid supply interruptions due to political crises and to permanently stay in touch with all relevant decision makers.
- *Strategic reserves for oil and gas*: Currently, the responsibility for keeping and managing strategic reserves of crude oil[57] and natural gas lies within the responsibility of each EU member country. The authors of EU (2001) propose a collaborative management and deployment of these reserves to minimize costs and optimize benefits for all member countries.
- *Development of transportation and transmission infrastructure to and within Europe*: The extension of infrastructure encompasses two major fields. First, there is the infrastructure required for transportation to Europe. This applies primarily to the natural gas supply, i.e. additional pipelines from the Russian, Caspian and also Persian Gulf gas fields, circumventing potentially unstable regions and offering additional transportation capacity, as well as the construction of more LNG regasification terminals in Europe to be able to source from other natural gas suppliers. Second, also the network infrastructure within Europe, both for natural gas and electricity, shall be upgraded and enhanced to allow better balancing of demand highs and lows within Europe.
- *Base level of domestic coal production*: Although domestic coal production cannot compete at world market prices, it has been proposed to limit the share of imported coal to 85 percent of total consumption. This would enable the EU to ramp up coal production if imports decline and also prevent the loss of coal production know-how in Europe.
- *Promotion of renewable energy sources*: An increasing share of energy from renewable, non-fossil and non-nuclear energy sources is regarded as one of the key methods to reduce the dependency on fossil fuels, also with regard to climate protection and compliance with the Kyoto emission reduction targets. The target is a twelve percent share of renewable en-

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[57] IEA member countries are committed to provide reserves of crude oil and certain oil products that cover at least the demand of 90 days, cf. EU (2001), p. 30. Many countries also keep strategic reserves for natural gas.

ergy sources in 2010, but recent EU publications indicate that only a share of at best nine to ten percent is likely to be reached (EU 2005a, p. 7).

- *Managing demand*: Above all, the key measure of the EU aims at reducing the overall energy demand by promoting energy efficiency programs and possibly additional taxation on energy consumption. The authors of the report EU (2005a) estimate the potential savings of this measure alone to reach 200 Mtoe annually, which is about one fifth of the total current energy consumption in Europe.
- *Intervention on financial markets*: It is suggested evaluating the possibilities of intervening activities on financial markets, thus attempting to reduce the volatilities of energy prices. With regard to the enormous financial volume of the transactions required to make a significant impact, it might be doubted if the European Union or any of its affiliates is the right institution for this task.

The long-term results of the above measures are highly uncertain. Politics remains the key source of uncertainty in this field. However, it is very likely that these measures will not affect fuel price levels on a global scale but only for European customers, either through higher sourcing costs or through higher taxation to influence demand patterns. The reasons why security of demand satisfaction is a critical issue at all are primarily of geopolitical nature and are discussed further below. It is obvious that there must be a certain trade-off due to a conflict of goals, especially when it comes to climate protection measures: Coal, being the fuel with the lowest probability of supply shortages, is instead the fossil fuel with the highest specific CO_2 emissions.

In an empirical model, the political target of guaranteed satisfaction of energy demand, i.e. a secure energy supply, can be reflected by limiting the share of individual fossil fuels per demand sector. Similarly, this approach can also reflect technical requirements of certain demand sectors (like a high share of oil products in the transportation sector) and the demand for consumer convenience, e.g. the preference of oil and gas over hard coal for domestic heating.

5.3 Other relevant factors and uncertainties

Beyond the key drivers discussed above that can be attributed to either the supply or demand side, there are numerous other drivers that also impact the price formation process of fossil fuels. In this section, the most relevant point are discussed.

Crude oil, due to its importance for the global economy, is again the fuel where the influence of these drivers is most obvious. However, also other fossil fuels are influenced by such drivers, the degree of influence being connected to the share of volume traded on the world markets.

5.3.1 Expectation formation and speculation

The existence of multiple uncertainties on the supply and demand side in connection with the asymmetric allocation of information among the market participants attracts traders and speculators like in every other commodity and financial market. This adds another dimension of uncertainty that is not related to supply or demand anymore but solely to the behavior of market participants.

Adelman (2002) comments that "*oil markets behave like financial markets, subject to panics, bubbles, and self-fulfilling swings. Speculators aim at profits, not by guessing right on the effects of supply and demand, but on guessing what others will guess, rightly or wrongly. OPEC behavior makes oil markets act like financial markets, because it generates more uncertainty to speculate on*" (p. 179). Of course, these are primarily short-term effects but some mid-term influences seem conceivable, especially considering the pricing of futures and forwards. An example for this can be found in the case of the Amaranth hedge fund that placed bets on the natural gas price spreads between summer and winter months. These bets covered the time span until 2012 (cf. e.g. Burton and Strasburg 2006). Once the large dependence of the fund on these positions became known, other market participants traded against them, finally leading to the collapse of the entire fund. In such a case, fuel prices become detached from fundamental supply and demand data and are primarily driven by market speculation, at least short-term. A similar example can be found in the case of the Bank of Montreal when a significant short position of the bank in natural gas trades drove prices up despite fundamental data indicating a price drop (cf. Lammey 2007).

Simmons (2005a) uses the example of the oil crisis in October 1973 to demonstrate the importance of market perception on fuel prices. He argues that the cutback in OPEC oil production turned out to be much smaller than announced as only Saudi-Arabia really reduced its production and Iran even tried to maximize its production to offset the reduction. In addition, the oil embargo only lasted for a few months. Despite this rather marginal supply shortage, prices soared and even kept climbing after the embargo had been ended: “*While this cutback amounted only to a tiny percentage of global production, it created a genuine panic that reverberated through all oil-consuming nations*” (Simmons 2005a, p. 54). The possibility of supply bottlenecks had suddenly got public attention and led to a lasting impact on prices.

In accordance with that, Dasgupta and Heal (1979) regard public perception of scarcity as a main driver of prices, especially for crude oil. They identify the year 1970, i.e. well before the first oil crisis, as turning point of public opinion. In the 1960s, there was a common agreement on an abundant oil supply for decades to come. In 1970, without any major event or significant shift in the supply-demand-balance triggering off that rethinking, scarcity became an issue in public perception, leading to gradually rising prices: “*One important and interesting point is that this change in market behaviour does not seem to correspond to any similarly sharp change in the economic forces underlying the market*” (Dasgupta and Heal 1979, p. 444). Dasgupta and Heal conclude that the lack of changes in fundamental data left only changes in market expectations to explain the new perception. Oil producers became more aware of their importance for a secure oil supply and oil consumers realized their exposure to the oil-producing countries.

The reverse effect could be observed in the late 1990s when the interpretation of the few information published by the OPEC made the market participants believe in abundant oil supply again. Due to statistical errors and misinterpretation, the market was convinced that existing oil reserves were far larger than reported which led to a period in which prices fell to 5 to 10 US-$ per barrel which is below the pre-crisis level in 1973 (cf. e.g. Economist 1999a and 1999b). This phenomenon became known as the *Missing Barrels*. After revealing better estimates of reserve and production capacities, crude oil prices tripled within 18 months (Simmons 2005a, pp. 82f.).

Dasgupta and Heal (1979) generalize these findings when they argue that the extrapolation of existing trends, a methodology often used in forecasting, tends to amplify these trends, especially in a risk-averse setting. If prices are low and are forecasted to remain low, natural resource owners will rather tend to sell at the current price instead of storing for later high-price periods. As a result, they contribute to a continuous low price level.

Ströbele (1987) describes another market pattern that can lead to price increases solely due to market expectations. Driven by an increasing demand and production capacities that are inelastic in the short run, prices start to rise. This leads market participants to expect further price increases and they start to hoard the resource to benefit from this development. The hoarded volumes worsen the already tight supply situation in the market and prices continue to rise. This vicious circle continues as long as the market expects further price increases. The initial price spike based on fundamental reasons is thus being amplified by expectations not based any longer on fundamental data.

He and Westerhoff (2005) develop a behavioral finance model in which they show that the presence of speculators in commodity markets increases the price volatilities. The implementation of strong reactions of the speculators, who could either follow a fundamental or a chartist approach, causes irregular switches between bullish and bearish market patterns.

In summary, it can be concluded that many of the uncertainties from market expectation and speculation originate from the uncertainties of the fundamental trends. Very quickly, the question arises whether and to what degree markets are efficient or not. Perman, Ma et al. (2003) comment that "*no resource does possess a complete set of forward markets, and in these circumstances there is no guarantee that agents can or will make rational supply decisions*" (p. 526). Closely related to that is the field of Behavioral Finance, where the impact of expectations and emotions on market decisions are investigated. Although of considerable interest, they shall not be further discussed here, as the focus of this thesis is on long-term developments[58].

5.3.2 Geopolitical, social and natural factors

Since the beginnings of global trading of natural resources, prices have always been exposed to political and other non-economic key drivers like natural disasters. Ströbele (1987) refers to a school of thought that regards the economic factors as very imprecise[59], allowing for a broad range of price and volume developments. The actual market action is then more determined by political events.

The most prominent examples to be quoted are again the two world oil crises in 1973/ 74 and 1979/ 80. In the first instance, Saudi Arabia announced a ten percent reduction of its oil production and an embargo regarding all oil shipments to

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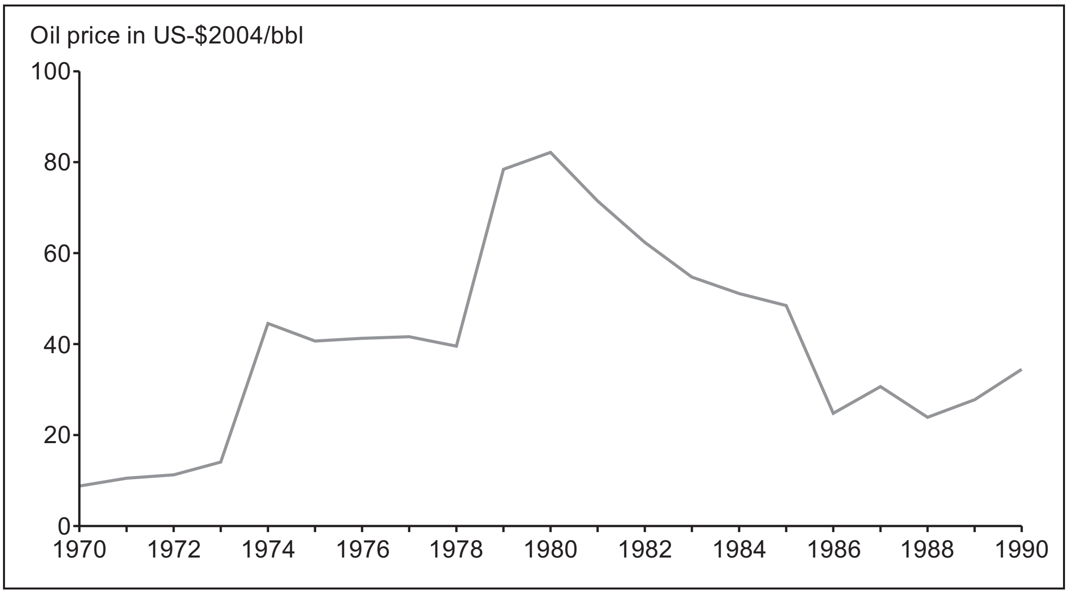
[58] In-depth discussions of Behavioral Finance subjects that can be transferred to fossil fuels can be found in the publications of Richard H. Thaler and Daniel Kahneman (cf. e.g. Thaler 1992 and Kahneman 1982, 2000). For an introduction into the theory and discussion of efficient markets, the reader is referred to the work of Eugene F. Fama, Werner F. M. DeBondt and again Richard H. Thaler (cf. e.g. Fama 1970, 1991, as well as DeBondt and Thaler 1985, 1987).

[59] Ströbele (1987) does not name the school of thought explicitly but only mentions the existence of one (p. 96).

the U.S.A. and the Netherlands. This was triggered by a decision of the U.S. government to support the rearmament of the Israeli army. Other Arabian countries announced to cut their oil production by five percent. The Arabian embargo was probably the first time that oil was used to apply political pressure on a global scale. Prices quadrupled within days and never fell back to their pre-1973 levels (cf. Fig. 5-22). Nordhaus, Houthakker et al. (1973) comment that "*the past months have demonstrated vividly that oil mixed with politics is a volatile brew*" (p. 564). The second oil crisis was caused by the Iranian revolution in 1979 and the subsequent reduction of the Iranian oil production to one-third of the pre-revolution level. Things got even worse when war broke out between Iran and Iraq.



Source: Own representation based on BP (2006)

Fig. 5-22: Impact of 1973/74 and 1979/80 oil crises

Besides the immediate influences on the supply situation of oil, these events also impacted the public opinion and the long-term expectations of the market participants (cf. previous subsection): "*Conventional energy wisdom turned on a dime and suddenly decided that oil was now permanently scarce, that demand growth was unstoppable and that the OPEC's power over the global economy was beyond any level of resistance*" (Simmons 2005a, p. 63).

Since then, the responsiveness of oil prices to political events has been demonstrated many times. The Persian Gulf area, being the key supplier for crude oil, has been and continues to be a major source of geopolitical uncertainty and in-stability. Each considerable incident in this area directly impacts the oil price. Regarding the time of persistency of the price shocks, the two major oil crises still stand out. Of course, there are many other geopolitical events outside the Gulf area that also influence oil prices. For the sake of conciseness, they will not be discussed here in detail.

Natural gas has also been used as a political weapon recently. The Russian Gazprom which is said to be closely linked to the Russian government, stopped natural gas deliveries to Ukraine when negotiations about prices failed in December 2005. Political observers suspect that disagreements about prices were only one side of the coin: They reckon that the Ukrainian elections, which resulted in a change of government and shifted the focus from a pro-Russian to a more Europe-oriented position, were the true reason for the drastic increase of the requested price. In the negotiations, Gazprom had suddenly demanded US-$ 220 to 230 per 1000 Nm^3 instead of US-$ 50 which had been contractually guaranteed until 2009. The political background became even more obvious by the fact that other, Russia-loyal countries were still granted a price around US-$ 50 per 1000 Nm^3 (cf. e.g. Aslund and Karatnycky 2005 and Agence France Presse 2006). While the direct impacts on global prices were presumably negligible in a long-term perspective, this behavior damaged Russia’s reputation as reliable supplier perhaps leading to long-term consequences in the European demand patterns and might thus influence long-term price trends indirectly, e.g. by a growing interest in nuclear fuels for power generation (cf. e.g. Curtin and Thomas 2006).

Another politics-driven key driver is the risk of or even the actual enforcement of expropriation or nationalization of private mining companies. Hersh (1979) reports that in a U.S. Senate hearing, evidence was presented that the fear of nationalization of the then American-owned oil producer Aramco led to a systematic overproduction of the company’s oil wells in Saudi Arabia. Overproduction of an oil deposit may lead to significant decreases in the total producible volume, thus impacting the long-term fuel availability and prices. Adding to that, fears of expropriation or nationalization hamper private investments in production capacities. Recent examples of similar incidents can be found in Bolivia and Russia. In the case of the Bolivian crude oil and natural gas production that became nationalized in May 2006, foreign companies might not be compensated for their investments that are now state-controlled (cf. e.g. Spiegel Online 2006 and White 2006). In Russia, the presumably state-controlled Gazprom bought the controlling stake of the Sakhalin 2 oil and gas development project from Royal Dutch Shell and two Japanese companies. The transaction had been preceded by political and regulatory pressure on the Western operators. Gazprom paid about 60 percent of the total investment costs of 12 billion US-$ so far which makes some market observers call the deal the "*first effective nationalization of a large foreign oil or gas project in Russia*" (Kramer and Myers 2006).

Ströbele (1987) proposes to include the probability of expropriation μ in the calculation for the appropriate discount rate r' (also cf. the next sub-section):

$$r' = r + \mu \qquad \forall \mu > 0 \tag{5.15}$$

Another key driver that falls into the category of (geo-) political and social events is for example the fear for terror, both on a global and on a regional level. As an example, private investors shy away from increasing their oil-related activities in Nigeria due to the repeated assaults on employees and facilities in the region. In an auction of oil exploration licenses in May 2007, the Nigerian government was only able to sell about half of the licenses on offer. It is estimated that reduced investments and operation interruptions after terrorist attacks reduced oil production in Nigeria by about 200 million barrels in 2006, after all equaling about 0.75 percent of the total global oil production (cf. e.g. BBC 2007 as well as Paul and Pandey 2007).

Natural disasters also can influence prices for fossil fuels, although their impact is likely to be more short-termed than the political events discussed above, assuming that repairing the damages to production facilities is rather a question of months than of years. The hurricanes "Rita" and "Katrina" in the Gulf of Mexico temporarily took out over 70 percent of oil production and nearly 50 percent of gas production in the Gulf, leading to price spikes for crude oil, natural gas as well as refined products (cf. e.g. Spiegel Online 2005a, 2005b and Healey 2005).

5.3.3 Interest and exchange rates

The importance of the interest rate r for decisions about resource extraction becomes obvious in the basic Hotelling equation (5.1) where it determines the net present value of the resource stock and thus the optimal depletion rate. Even if one dismisses Hotelling's underlying assumption of scarcity, in an intertemporal consideration the interest rate plays a crucial role for discounting any future cash flows to the present.

Ströbele (1987) explains the importance of the interest rate for resource-exporting countries. Producers that are able to invest the revenues from resource exports at high interest rates will tend to charge lower prices to maximize their current proceeds. If the investment opportunities, e.g. in domestic capital equipment and infrastructure, are limited, producers will instead tend to demand higher prices to save their natural resources for the future. This can also explain why some oil-exporting countries have reduced their production in periods of high oil prices: They did not have the economic capability to absorb the higher revenue streams in a sustainable way, leading to a paradox price-supply curve (cf. Ströbele 1987, pp. 54 and 95).

For private investors, also taxes on capital gains τ impact the interest rate, as this type of tax[60] reduces their after-tax rate of return r_a (cf. equation 5.16). Private investors will therefore adjust their internal interest rate to compensate this reduction.

$$r_a = r(1-\tau) \tag{5.16}$$

When discussing the results of models for climate change-related costs, the climate economist Richard Tol describes the interest rate as "*possibly the most important parameter*" (quoted in Voss 2007). Although the aims and objectives of this thesis are somewhat different from climate change models, the importance of the interest rate might be similar, at least with regard to investment decisions.

The uncertainty related to the interest rate is two-dimensional: First, the resource owner has to determine the appropriate level of the rate. Nordhaus, Houthakker et al. (1973) point out that the interest rate for investments must compensate for all risks incurred in the process of resource production and sales, e.g. price volatilities, changing demand patterns, competition and also the advent of a backstop technology. Thus, it is obvious that the calculation of an accurate interest rate for an investor can at best be an educated guess, based on experience and benchmarks from other projects, always leaving a certain degree of uncertainty in the calculation.

The second dimension related to interest rates is the development over time, especially given the high investment costs and long amortization periods for natural

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[60] One other important type of tax is the constant sales tax or royalty tax per unit. It can also come with a negative sign and is then called subsidy. Its impact on the optimal depletion pattern is the same as an increase (or decrease) in extraction costs and is therefore not discussed any further here. Cf. e.g. Dasgupta and Heal (1979), p. 361ff. for a more detailed discussion.

resource exploration, development and production. If one of the assumptions used to calculate the appropriate interest rate for an investor changes over time, the interest rate must be adjusted. Obviously, this is not possible ex ante.

Currency or exchange rate effects are also a major source of uncertainty for future fuel price developments in Europe. While international trade contracts for oil, coal and gas are placed in US-$, European utility companies usually will calculate in Euro. Looking back into the relatively short history of the Euro to US-$ exchange rate, annual averages varied between 0.827 and 1.5805 €/US-$ from the introduction of the Euro in 2000 until 2008 (Federal Reserve Board 2008). It is obvious that such fluctuations can significantly impact the fuel price costs of a European electricity producer.

5.4 Implications for this thesis

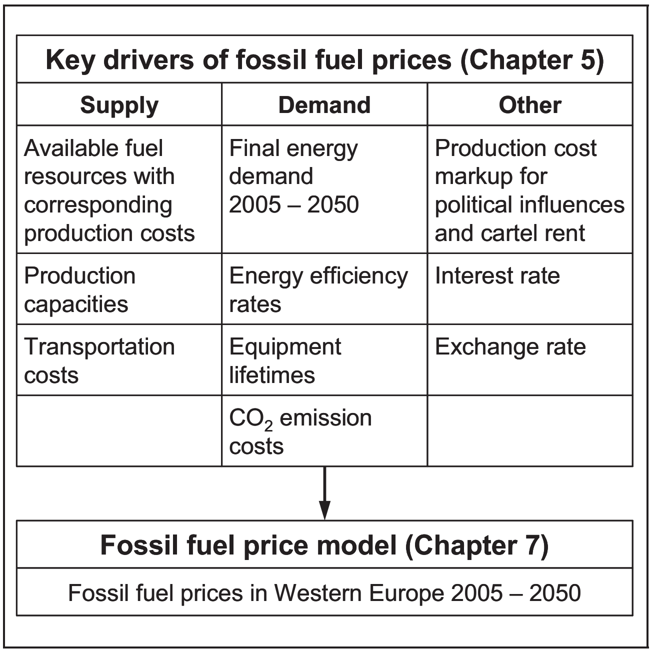
In this chapter, various key drivers on fossil fuel prices have been introduced. Also, the reasons and effects of the appendant uncertainties have been explained. As it is hardly possible to include all key drivers into a fundamental model due to complexity and data constraints, a selection of the most important drivers needs to be made.

On the supply side, available fuel resources are a key element of fundamental modeling as the review of fuel availability in chapter 4 and the discussion on scarcity and marginal product cost in the subsections 5.1.1 and 5.1.2 show. Related to that, also production capacities, split by fuel and region, play an important role as sufficient capacities in each period are a prerequisite to satisfy energy demand. A lack of sufficient production capacities will drive fuel prices. Finally, also transportation cost need to be reflected in a fundamental model to appropriately reflect fuel shipments between various regions.

On the demand side, final energy demand is the key driver of the resource volumes that need to be produced per period. To calculate the primary energy demand and thus the resource volumes, also energy efficiency rates are required. To appropriately reflect the long-term substitutability (cf. subsection 5.2.3) between fossil fuels, equipment lifetimes can be used as a proxy, indicating how long investments in certain technologies determine the demand for a specific fossil fuel. To consider the impact of fossil fuels on the global climate, also CO_2 emission costs need to be included.

In addition, the impact of political activities, including cartelization, can only be partially reflected in a fundamental model. Thus, a production cost markup is applied to allow for these key drivers. Interest and exchange rates are mandatory elements of any global economic model.

Fig. 5-23 provides a schematic overview on the key drivers of fossil fuel prices that have been identified to be relevant in this chapter.



Key drivers of fossil fuel prices (Chapter 5)

Supply	Demand	Other
Available fuel resources with corresponding production costs	Final energy demand 2005 – 2050	Production cost markup for political influences and cartel rent
Production capacities	Energy efficiency rates	Interest rate
Transportation costs	Equipment lifetimes	Exchange rate
	CO_2 emission costs	

Fossil fuel price model (Chapter 7)

Fossil fuel prices in Western Europe 2005 – 2050

Source: Own representation

Fig. 5-23: Input data for fossil fuel price model

As the purpose of this thesis is to develop an empirical model reflecting the impact of the above key drivers on fossil fuel prices, a short reflection on the role and possibilities of modeling in economics seems appropriate at this point before reviewing adequate modeling concepts in the next chapter.

The discussion on the self-understanding of modern economics in general and the validity of economic models in particular goes back to Mill (1836) who describes economics as an inexact science, applying deductive methodologies for the empirical confirmation of theories. This refers to the fact that, despite constant efforts for formalization and axiomatic construction, economics is not an exact science to the same degree as natural sciences, where unambiguous natural laws allow the reliable and repeatable computation of e.g. trajectories, temperatures or pressures. Contrary to that, economics as an inexact science does not allow for accurate and precise calculations or predictions but can only provide rather qualitative insights. One of the key reasons here is that economics does not possess natural laws and constants like e.g. the laws of thermodynamics or the gravity constant. On the contrary, human behavior as one of the key determinants is far from being constant, reliable and certain.

Since the initial publication of Mill (1836), the role and underlying philosophy of economics has been widely discussed. As a recapitalization of the entire philosophical debate would exceed the scope of this thesis, the interested reader is referred to Hausman (1998) for a comprehensive overview.

Overall, it can be said that the modeling of economic interrelations and formulation of economic laws requires simplifications and assumptions. Keeping that in mind, the purpose of an economic model – contrary e.g. to the calculation of a trajectory parabola in physics – cannot be the calculation of an exact forecast but rather the deduction of general trends and qualitative insights.

In general, economists do not deny that their models contain a significant share of simplification but they do not regard this as a deficit: "*A model which took account of all the variegation of reality would be of no more use than a map at the scale of one to one*" (Robinson 1962, p. 33, also cf. Janich 2002, p. 30)[61]. Especially for models with a time span of several decades, economists agree that reliable forecasts are hardly possible, given the degree of uncertainty and shortcomings of economic laws (cf. Voss 2007). Thus, quantitative models are frequently used, mostly not for exact forecasts or prediction, but rather to generate improved qualitative insights[62]. Looking ahead, it should be kept in mind that the results of this thesis are not meant to be precise forecast of prices but rather the description of possible developments.

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[61] In support of this, Sterman (1991) writes: "*The usefulness of models lies in the fact that they simplify reality, putting it into a form that we can comprehend. But a truly comprehensive model of a complete system would be just as complex as that system and just as inscrutable. The map is not the territory – and a map as detailed as the territory would be of no use (as well as being hard to fold)*" (p. 211).

[62] Böhringer (2004) refers to the application of computable economic models as "*theory with numbers"* (p. 15).

6 MODELING APPROACHES

Based on the qualitative discussion of key drivers on fossil fuels prices in the previous chapter, the quantitative aspect of this thesis is now targeted, i.e. the development of an own modeling approach. This chapter lays the foundation for the subsequent model formulation by reviewing different model types and modeling techniques as well as their advantages and inconveniences, particularly when it comes to modeling fuel prices in the perspective chosen here. These considerations serve as basis for an own modeling approach.

The first sections of this chapter provide an overview on model types and techniques with particular emphasis on fundamental models, stochastic modeling and linear optimization. Another section is dedicated to the discussion of model risks and model validation. At the end of this chapter, selected models dealing with fossil fuel prices are presented and discussed. These models serve as references with regard both to modeling techniques as well as results.

6.1 General model categorizations

In this first section, general model categories are introduced. Each of the following subsections describes a relevant dimension for the definition of an own modeling approach.

6.1.1 Analytical and numerical approach

There are two different methodologies that can be applied for mathematical modeling. The analytical approach is based on a framework of closed formulas, e.g. continuous stochastic differential equations, which describe the development of prices over time. The application of an analytical approach requires that all model parameters are known or can be estimated, and that the formula may be solved analytically for the variable of interest. Then the reliable computation of results becomes possible.

However, complex economic relationships cannot always be described with a set of formulas with closed-form solutions[63]. In these cases, numerical approaches, e.g. iterative computation, may be applied.

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[63] Hull (2006) refers to American options as an example where analytic valuation is not possible. Contrary to European options, American options can be exercised not only at the maturity date but at any point between purchase and maturity.

6.1.2 Static and dynamic models

This criterion describes the role of time in a model. In a static model, time is not a relevant dimension, i.e. all decisions fall into the same period. In dynamic models, the decision variables are also described as a function of time. Possible decisions in a given period depend on decisions from previous periods (e.g. capital investments that have been made in earlier periods and determine the available production capacities) and will influence decisions in future periods.

6.1.3 Deterministic and stochastic models

In a deterministic model, all parameters are known with certainty. If some or all parameters are uncertain or unknown and need to be estimated, e.g. by applying a probability distribution, the model type is referred to as stochastic (cf. e.g. Birge and Louveaux 1997 and Winston 2004). This method is often used to reflect uncertain future developments, e.g. in the real options approach by Dixit and Pindyck (1994) (cf. subsection 3.2.2.3). Some techniques for stochastic modeling are introduced later in this chapter.

6.1.4 General and partial equilibrium models

In economics, the concept of equilibrium was probably introduced by Isaac Gervaise (cf. Brodbeck 2000): "*That if Trade was not curbed by Laws, or disturbed by those Accidents that happen in long Wars, etc. which break the natural Proportion, either of People, or of private Denominators; Time would bring all trading Nations of the World into that Equilibrium, which is proportioned, and belongs to the number of their Inhabitants*" (Gervaise 1720). Today's understanding of general equilibrium models goes back to the work of Léon Walras and Vilfredo Pareto at the end of the 19th century. Their early neoclassical school of thought, known as the *Lausanne School*, postulates that prices and production of all economic goods are connected to each other. There cannot be a change in price or supply of one product or in one market without affecting all other prices and volumes. Walras and Pareto try to capture the interdependencies of all economic variables in a system of concurrent equations. They regard this approach as superior to the isolated consideration of selected elements and correlation where all other values are assumed to be ceteris paribus constant, thus eliminating their explanatory power (cf. e.g. Lange 1932).

Arrow (1974) defines *general equilibrium* as follows: There is at least one set of prices, one per economic good, which balances the supply and demand for all economic goods. If supply and demand do not balance, prices and thus volumes will change until the balance is reached. If supply and demand are balanced, prices will not change further and the state of equilibrium is reached. The equilibrium is called general because of the inclusion of all economic goods. The general equilibrium cannot be decomposed into separate equilibria for distinct economic goods. It is Pareto-efficient, i.e. there is no other allocation of goods that leaves every market participant at least as well off while making one party better off. However, this does not imply a morally correct distribution of goods in a sense that there are no large discrepancies between rich and poor.

Regarding prices, a general equilibrium does not offer a unique solution since any positive multiple of all prices also constitutes a valid solution. This is based on the work of Jean-Baptiste Say. He postulates that the amount of money in circulation is neutral in its effect on the economy. The amount of money only impacts the level of prices but not the relation of price levels of the economic goods. Say's Law of Markets (cf. e.g. Stobbe 1987, p. 366) also posits that there will not be a significant overproduction of goods which is consistent with the principle of the general equilibrium: "*The general equilibrium of the economy is then the set of prices which equate all excess demands to zero*" (Arrow 1974, p. 258).

Arrow (1974) emphasizes that the sheer existence of a system of equations describing the equilibrium does not prove the solvability of the problem. This requires a convex set of consumption vectors as well as convex vectors of feasible production[64].

The concept of general equilibrium is built on some implicit assumptions: Perfect rationality of individuals, i.e. an optimizing behavior of all market participants, perfect information as well as perfect competition is implied.

General equilibrium models come to their limits when problems of specific industries or commodities are to be analyzed (cf. e.g. Lange 1932). To tackle this type of problems, it is necessary to detach the economic goods under consideration from the overall framework of a general equilibrium framework. The reduced system of equations contains only the formal description of the relevant economic goods and their interrelations. All other economic parameters are assumed to be ceteris paribus constant. Such a system of equations is called *partial equilibrium* and constitutes a special case of a general equilibrium. Walrus and Pareto regard such partial or isolated frameworks as inferior to their general approach. Their

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[64] Cf. Arrow (1974), p. 264f. This also bars the realization of economies of scale in production.

dismissive attitude kept them from realizing the benefits of partial equilibria: "*Diejenige wirtschaftstheoretische Schule, der wir die scharfsinnigsten Konstruktionen der modernen Wirtschaftstheorie verdanken, hat fast gar nichts zur Lösung und Fortentwicklung der besonderen Probleme der Wirtschaftstheorie beigetragen*" (Lange 1932, p. 56).

Böhringer (1996), (1998) notes that general equilibrium models have their weaknesses in reflecting short-term adjustment processes caused by imperfect markets. However, if used for long-term analyses, this insufficiency can be neglected.

6.1.5 Simulation and optimization

Simulation and optimization techniques are among the most common approaches to formulate and solve equilibrium models (cf. Böhringer 1996, 1998). This subsection briefly introduces the two methods and explains the key characteristics and differences[65].

In a simulation, the solution is described by a set of simultaneous equations. Inequalities are transformed into equations by introducing slack or excess variables (cf. Böhringer 1996, p. 49, and Winston 2004, p. 128). The *Newton gradient method* (cf. e.g. Bartsch 1994, p. 122, and Poddig, Dichtl et al. 2003, pp. 598ff.) and the *Gauss-Seidel method* (cf. e.g. Bartsch 1994, pp. 159ff.) are common solution algorithms for simulation-based equilibrium models. In equilibrium models, the simulation approach allows for concurrent treatment of prices and volumes or activities, e.g. for the implementation of different customer preferences or segments. However, the definition of upper or lower bounds for prices or volumes is not possible as this would require the usage of inequalities (cf. Böhringer 1996, p. 52).

In general, a simulation thus primarily aims at (e.g. technical) feasibility but without any guarantee of achieving a (cost-) optimal solution. It follows that a simulation is primarily descriptive, i.e. it "*does not calculate what should be done to reach a particular goal, but clarifies what would happen in a given situation. The purpose of simulations may be foresight (predicting how systems might behave in the future under assumed conditions) or policy design (designing new decision-making strategies or organizational structures and evaluating their effects on the behavior of the system)*" (cf. Sterman 1991, p.9).

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[65] As Böhringer (1996) pointed out, simulation and optimization techniques can be mixed and combined to eliminate the disadvantages of the respective approaches. He differentiated between a combination of simulation and optimization methods (heterogeneous approach) as well as sequential optimization and complementary problems (homogeneous approaches).

In an optimization problem, also inequalities can be considered and thus limitations to volumes or prices are possible. In return, optimization problems are not suitable for simultaneous constraints of prices and volumes, as this can result in infeasibilities (cf. Böhringer 1996, p. 55). Optimization models are also called prescriptive (cf. Winston 2004, p. 3), as they build on the definition of an optimal behavior for a given problem based on an objective function. A more detailed discussion of linear optimization can be found in section 6.4.

6.1.6 Theoretical and empirical approaches

In his categorization of electricity price models, Weber (2005b) distinguishes between theoretically and empirically based approaches (cf. Tab. 6-1). This categorization is not specific to electricity markets but can be used for other markets, too:

Theoretically founded models	**Empirically based models**
Fundamental models	Statistical models
Finance models	“Technical” analysis and expert systems
Game theoretical models	

Source: Own representation based on Weber (2005b), p. 32

Tab. 6-1: Categorization of model types

Of the theoretically founded models, fundamental approaches build on basic, primary data related to the underlying markets. This can include production costs and capacities, demand volumes, transportation costs, capacities etc. In principle, all key drivers on the supply and demand side discussed in sections 5.1 and 5.2 above fall into the category of fundamental data.

Finance models are primarily based on financial data, e.g. price spreads or volatilities. While analysis tools and methods applied for these model types were originally developed for applications in the stock markets, numerous transfers have been made into adjacent fields, e.g. to energy commodities prices (cf. e.g. Weber 2005b and Roggenstein 2005).

The third and last group of models in the first category deals with the analysis of strategic planning and reactions of market participants. They are based on game theory approaches. This group as well as the second category (empirically based models) will not be discussed any further here[66].

6.1.7 Conclusions for the own approach

At this point, an assessment regarding the setup of an own model that is to be developed in this thesis needs to be made, based on the above categorizations. Going forward, this will allow focusing the further analyses of this chapter on the specific topics that are relevant for the own model.

With regard to the discussion of key drivers for fossil fuel prices in chapter 5, the development of an analytical approach for fossil fuel prices seems hardly possible due to the complex and sometimes non-continuous interrelations between the individual key drivers. Thus, a *numerical* approach is chosen.

With regard to the time dimension, a *dynamic* model must be chosen, implicitly required by the objective to analyze price developments over time. The same holds true for the decision for a *stochastic* implementation as this is predetermined by the overall topic of the thesis as well.

As the focus of this thesis is limited to the supply and consumption of primary fossil fuels only, a *partial equilibrium* model is chosen, following the argumentation of Lange (1932) that partial equilibria are more suitable to analyze problems limited to specific commodities. Supporting that, Bergman (1988) finds in his review of energy modeling approaches that final energy demand is often implemented as an exogenously given parameter. In other words, energy system models are often designed as partial equilibria, using linear optimization to determine the optimal allocation of energy resources: "*An energy system model endogenously determines the cost-minimizing pattern of energy resource extraction, and conversion and energy distribution. The optimization normally incorporates energy conservation and fuel-switching activities within households and firms. Thus, although demand for 'useful energy' is exogenously determined, demand for commercial energy forms such as electricity, gas, and fuel oil is to some extent endogenously determined in a typical energy system model*" (Bergman 1988, p. 377).

The decision between a simulation and optimization model cannot be made that unanimously as in principle both approaches can be used for the purpose of this thesis. Both seem appropriate to assess the impact of stochastic changes in key

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[66] For a thorough discussion of model categories cf. Weber (2005b), pp. 32 - 78

drivers' values on fossil fuel prices. However, as only an *optimization* allows for the inclusion of inequalities and ensures the calculation of a cost-optimal solution, this approach is chosen.

With regard to the last model category in this section, a theoretically funded, *fundamental* model will be applied with the drivers discussed in section 5.4 as key inputs.

While some of the above categories and the implications of the choices made are self-explanatory and do not require further investigation, three methodical elements need to be reviewed in more detail: fundamental modeling, (linear) optimization and stochastic time series. Going forward, the following structure will be applied to discuss these three elements: First, fundamental modeling will be examined in more depth, looking into the sub-categories of this model type. Next, the key characteristics of stochastic time series will be reviewed. Finally, both deterministic and stochastic linear optimization will be discussed.

6.2 Fundamental modeling

Skantze and Ilic (2001) list four different types of models based on fundamental data: production-/ cost-based approach, equilibrium models, agent-based/ experimental models and stochastic-fundamental models. All four types are based on the assumption of balanced supply and demand volumes. Again, this categorization refers to electricity markets, but can be transferred to other commodity markets (cf. Skantze and Ilic 2001, pp. 57 - 60):

- *Production- or cost-based approach*: This model type builds on the bottom-up calculation of the cost structures on the supply side. The resulting cost-supply curve is matched with demand forecasts, leading to price estimates. This approach requires detailed information on cost structures of the market participants. In addition, it does not reflect the exercise of market power and is thus likely to deliver results below observed market prices.
- *Economic equilibrium models* (also cf. subsection 6.1.4) try to incorporate market power and strategic elements into cost-based approaches, e.g. by including price markups depending upon the degree of market concentration. Still, equilibrium models are likely to capture only a temporary snapshot of the market and neglect dynamic price patterns.

- *Agent-based and experimental approaches* attempt to further improve the reflection of strategic behavior of the market participants in the model. Each agent is defined by an objective function and model constraints. In this way, market dynamics can be observed very well. Model results are obtained by simulations with varying input parameters. However, the large flexibility of this approach also makes it difficult to obtain meaningful quantitative results, as calibration of the model parameters, i.e. the specification of decision rules for the agents, is extremely laborious. Thus, agent-based models are primarily used to qualitatively analyze strategic behaviors.

- *Stochastic-fundamental models* relate fundamental physical and economic factors to developments of the commodity price. By stochastically altering the values of these underlying fundamental drivers, the impact on the price formation process is analyzed. This approach is quite sensitive to the assumptions made about the economic relationship and restrictions in the market. This stochastic element will be further investigated in the next section.

6.3 Key characteristics of stochastic time series

As discussed in the previous chapter, each fundamental key driver contains an element of uncertainty related to the occurrence or value of the driver. To incorporate this uncertainty, stochastic processes can be modeled. Thereby, it is useful to review briefly basic characteristics of stochastic processes in order to arrive at an appropriate modeling of uncertainties.

6.3.1 Continuity in price and time

In general, price processes can be divided into continuous and discrete processes. Hull (2006) also distinguishes between continuity in value (e.g. price) and in time.

A *continuous-price* process is characterized by infinitesimally small price changes, i.e. not only discrete price changes are allowed. A process limited to discrete price changes is called *discrete-price* (cf. Hull 2006, p. 326). If the time lag between two consecutive data points is infinitesimally small, the time series is characterized as *continuous-time* process. If a time lag can be observed, the process is referred to as *discrete-time*.

6.3.2 Stationarity of time series of prices

One of the key characteristics is *stationarity* of a time series. Without stationarity, a regression analysis might lead to spurious results.

Poddig, Dichtl et al. (2003) distinguish between three types of stationarity. The first, mean-stationarity, describes the fact that the expected value E of a price p_t is constant over time:

$$E(p_t) = \mu \qquad \forall t \tag{6.1}$$

Variance-stationarity applies if all prices show the same variance *Var*:

$$Var(p_t) = \sigma^2 \qquad \forall t \tag{6.2}$$

If the covariance *Cov* between two data points in time only depends on the length of the period k, the time series is covariance-stationary:

$$Cov(p_t, p_{t-k}) = \sigma_k \qquad \forall t, k \tag{6.3}$$

A time series must fulfill all three conditions to allow for meaningful and unbiased data analysis. It is then called *weakly stationary*, i.e. all three measures are time-independent.

In other words, any time series used e.g. for a regression analysis needs to be cleaned from inherent trends[67]. As one of the simplest methods, the differences between the values in *t* and *t-1* rather than the actual values may be used (cf. Poddig, Dichtl et al. 2003, p. 362).

Variance-stationarity is also referred to as homoscedasticity, e.g. when the residual values of a regression analysis exhibit a Gaussian distribution. Also, a time series with constant volatility is labeled as homoscedastic. Variance-instationarity is called heteroscedasticity, time series with time dependent volatility are heteroscedastic.

A common way to test for weak stationarity is the *Dickey-Fuller test*[68]. It is built on the assumption that an autoregressive process (cf. subsection 6.3.3) of the order one exists:

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[67] In literature, deterministic and stochastic trends (e.g. in a random-walk series) are distinguished, cf. Poddig, Dichtl et al. (2003), p. 361ff.

[68] Also referred to as *unit root test*.

$$p_t = \beta_0 + \beta_1 p_{t-1} + \varepsilon_t \tag{6.4}$$

Here, price p_t is composed of a constant term β_0, a share of the previous year's price p_{t-1}, weighted by the regression coefficient β_1, and a white noise term ε_t.

Transformation of equation (6.4) leads to

$$\Delta p_t = \beta_0 + \delta \cdot p_{t-1} + \varepsilon_t \quad \text{with } \delta = \beta_1 - 1 \tag{6.5}$$

The test is specified with the null hypothesis that the time series is non-stationary, i.e. $\delta=0$, vs. the alternative hypothesis of stationarity ($\delta<0$). δ is calculated using an OLS estimate with a regression model based on equation (6.5). If the result for δ is smaller than the Dickey-Fuller critical value (cf. Poddig, Dichtl et al. 2003, pp. 771f.), the null hypothesis can be rejected.

6.3.3 Autocovariance and autocorrelation

Autocovariance and *autocorrelation* describe the intertemporal dependencies within a given time series of prices. They define the impact of past data points on the next value. For weakly stationary time series[69], the autocovariance γ_k is calculated as

$$\gamma_k = Cov(p_t, p_{t-k}) \qquad \text{with } \forall t \tag{6.6}$$

and the autocorrelation ρ_k as

$$\rho_k = \frac{Cov(p_t, p_{t-k})}{Var(p_t)} \qquad \text{with } \forall t\,. \tag{6.7}$$

k, the time lag of the series, indicates the order of the autocorrelation, i.e. the time period to which element the relationship exists.

6.3.4 Probability distribution

In stochastic modeling, the probability distribution describes the likelihood of a value being assigned to a parameter. This is particularly important for the residual values, i.e. the fraction that cannot be explained by the applied equation or

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[69] For time series that are not weakly stationary, a time index has to be added to the formula, cf. Poddig, Dichtl et al. (2003), p. 98.

model. They should follow a probability distribution that needs to be estimated by the modeler.

Frequently, the following three types of probability distributions are used for this purpose: Gaussian, Poisson and binomial/ trinomial. In rather rare cases, e.g. if not enough data points for an accurate parameter estimation for a Gaussian distribution are available, also triangular distributions are used. While Poisson processes are used to model price jumps[70], Gaussian distributions are used to model the common price fluctuations and uncertainties.

Detailed descriptions of each probability distribution can be found in the standard literature on statistics and econometrics (cf. e.g. Schlittgen 2003 and Poddig, Dichtl et al. 2003) and will not be discussed here any further.

An important phenomenon occurring in empirical distributions is *leptokurtosis* (cf. Poddig, Dichtl et al. 2003, p. 130 and 143), also known as the existence of *fat tails*. It describes the fact that a data set, e.g. the returns of commodity prices, comprises more data points with an extreme low probability of occurrence than a Gaussian probability distribution would suggest. This is due to the existence of price jumps or spikes that are not represented in a regular Gaussian distribution.

A data sample can be tested for the existence of a Gaussian distribution using the *Jarque-Bera test*[71]. The test setup is based on the skewness S and kurtosis K of the data sample that is to be tested. *Skewness* describes the degree of (a-) symmetry of the probability distribution or data sample, whereas *kurtosis* measures whether the variance of the data sample is due to a small number of extreme deviations or to a larger number of moderate deviations.

The skewness S of the estimated residual values $\hat{\varepsilon}_t$ is defined as (cf. Poddig, Dichtl et al. 2003, p. 335):

$$S = \frac{\frac{1}{n}\sum_{t=1}^{n}(\hat{\varepsilon}_t^3)}{s^3} \qquad \text{with } s = \sqrt{s^2} \text{ and } s^2 = \frac{1}{n}\sum_{t=1}^{n}\hat{\varepsilon}_t^2 \tag{6.8}$$

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[70] A *price jump* refers to a sudden large change in price from one point in time to the next with a magnitude significantly beyond normal volatility of the time series. It can have either a positive or a negative sign, and the price does not immediately revert to its long-term average. Contrary to that, a *price spike* is a jump that is followed by a jump with about the same magnitude but in the opposite direction in the next period.

[71] Cf. Poddig, Dichtl et al. (2003), p. 333ff., for a detailed discussion of the Jarque-Bera test.

For a perfectly symmetrical Gaussian distribution, S is zero. A distribution skewed to the right results in $S>0$, a left-skewed distribution in $S<0$.

The kurtosis K is calculated by

$$K = \frac{\frac{1}{n}\sum_{t=1}^{n}\hat{\varepsilon}_t^4}{s^4} \tag{6.9}$$

In a perfectly symmetrical Gaussian distribution, K will take the value 3. A larger result for K indicates the existence of few extreme deviations in the data sample, while a small K value indicates few deviations.

The Jarque-Bera statistics is a test against the null hypothesis that the tested data set follows a Gaussian distribution. It is defined as

$$JB = \frac{n-(k+1)}{6}\left(S^2 + \frac{1}{4}(K-3)^2\right) \tag{6.10}$$

n is the number of data points in the set, and k the number of explanatory variables in the regression model used for the estimation of the residual values[72]. Based on the values for a symmetrical Gaussian distribution of zero for S and three for K, the JB value of such a distribution will have the value zero, too. Thus, small values for JB support the null hypothesis. For exact results, the result of the Jarque-Bera test statistics needs to be smaller than the value resulting from a χ_2^2 distribution (with 2 degrees of freedom) with the chosen probability of error[73].

6.3.5 Random-walk process and the Markov property

A basic process for the description of a time series of the price p in the period t is a *random-walk process*. It is characterized as (cf. Poddig, Dichtl et al. 2003, p. 111):

$$p_{t+1} = p_t + \varepsilon_{t+1} \tag{6.11}$$

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[72] If the Jarque-Bera test is not used to test residual values, but to test other time series, the term *k+1* is set to zero, leaving only *n* in the numerator of the first term (cf. Poddig, Dichtl et al. 2003, p. 339).

[73] For economic analysis, a 5 percent probability of error can be seen as default value, cf. Poddig, Dichtl et al. (2003), p. 344.

where ε_t (referred to as *white noise*) is weakly stationary. Hence, the expected value *E* and the covariance *Cov* are equal to zero. Also the variance *Var* must be constant:

$$E(\varepsilon_t) = 0\,,\ Var(\varepsilon_t) = \sigma^2\,,\ Cov(\varepsilon_t, \varepsilon_{t-k}) = 0\,.$$

The random-walk process as a whole is non-stationary. When considering the change Δp_t in price from one period to the next, Δp_t can be described as the product of a random variable ε and the square root of the length of time considered (cf. Weber 2005b):

$$\Delta p_t = \varepsilon \cdot \sqrt{\Delta t} \tag{6.12}$$

If the price in *t+1* only depends on the value in *t*, with any data points further back in time not influencing the future developments, this time series of prices satisfies the *Markov property* (cf. Hull 2006). In a discrete-time environment, such processes are also called *Markov chain* (cf. e.g. Meyn and Tweedie 1993 and Winston 2004).

6.3.6 Mean-reversion

A phenomenon described e.g. by Gibson and Schwartz (1990), Deng (2000) as well as Weber (2005b) is that energy commodities prices tend to revert to a long-term mean price level. "*When the price of a* [energy] *commodity is high, its supply tends to increase thus putting a downward pressure on the price; when the spot price is low, the supply of the commodity tends to decrease thus providing an upward lift to the price*" (Deng 2000, p. 5). With regard to electricity in particular, Weber (2005b) infers that the events triggering a price spike are only of temporary nature. Thus, the prices fluctuate around an average price with stochastic deviations.

Mathematically, the mean-reversion process can be described as

$$\Delta p_t = \kappa(p_0 - p_t)\Delta t + \sigma\varepsilon\sqrt{\Delta t} \tag{6.13}$$

or for the logarithms of prices

$$\Delta \ln p_t = \kappa(\ln p_0 - \ln p_t)\Delta t + \sigma\varepsilon\sqrt{\Delta t} \tag{6.14}$$

The mean-reversion rate κ determines the speed at which the time series reverts to its long-term average and is always larger than zero. Clewlow and Strickland (2000) point out that the mean-oriented readjustment of a time series does not necessarily take place immediately. Instead, if the stochastic term in the second summand in equations (6.13) and (6.14) is larger than the mean-reverting first summand and has the opposite sign, the time series will move even further from the mean value. Also, since the mean-reversion process actually is a continuous process (cf. Clewlow and Strickland 2000, p. 18), a discretization as used in the equations (6.13) and (6.14) is only valid, if the time step Δt is relatively small compared to the speed of mean-reversion.

The speed of mean-reversion is measured by the half-life $t_{½}$ of the process. Clewlow and Strickland (2000) define half-life as "*the time taken for the price to revert half way back to its long-term level from its current level if no more random shocks arrive*" (p. 20):

$$t_{1/2} = \frac{\ln 2}{\kappa} \tag{6.15}$$

Considering the constraint that no further random shocks are permitted, $t_{½}$ is a calculated average value that is hardly achieved in reality. For a correct discretization of a mean-reverting process, equation (6.16) must apply:

$$\Delta t << t_{1/2} \tag{6.16}$$

De Jong and Huisman (2002) note that mean-reverting models perform quite favorably for the modeling of oil and gas prices. They are less suitable for electricity price processes since mean-reverting models are not able to mirror extreme price spikes as they occur in electricity markets.

6.4 Linear optimization

Based on the conclusions from section 6.1, the model being developed in this thesis will be formulated as optimization problem. In this section, the basic principles of optimization will be reviewed, starting with deterministic optimization, i.e. with all parameters being known and certain. After that, the focus is extended to stochastic optimization with uncertain or unknown parameters. The focus of this section will be limited to linear problems only, it does not consider other optimization models like nonlinear programming (NLP)[74] or mixed complementary problems (MCP).

6.4.1 Formulation of a deterministic optimization problem

The output of an optimization model can be described as a set of decisions that leads to an optimal solution, e.g. by meeting a given target with the lowest cost possible or by realizing the maximum profit based on a defined stock of goods. Optimization models are thus called *normative* or *prescriptive*, as "*they tell you what to do in order to make the best of the situation*" (Sterman 1991, p.4). In one of their simplest forms, optimization models can be formulated as linear programming (LP) problems, a concept going back to Kantorovich (1939) and Dantzig (1949).

LP problems are composed of three elements: a linear objective function, decision variables and linear constraints. The objective function defines the quantity to be optimized. Decision variables are the variables that are under control of the decision maker, impacting the result of the system being optimized. Constraints impose restrictions on the possible values of the decision variables, i.e. they define the feasible region for the variables' values. Constraints can be defined as equalities or inequalities[75]. The overall purpose of an LP model is to calculate a set of decision variable values with an optimal result of the objective function, satisfying all constraints. Depending on the economic meaning of the objective function, the optimal solution of an LP problem is either a global minimum (e.g. for costs) or a global maximum (e.g. for profits). A LP problem can have no, one or an infinite number of solutions (cf. Winston 2004, p. 55).

It can be written as

$$\begin{aligned} &\min c^T x \\ &\therefore Ax \geq b \\ &\quad x \geq 0 \end{aligned} \tag{6.17}$$

The first line defines the linear objective function with the decision variables x_i. The values of the decision variables must satisfy the set of constraints in the second line of equation (6.17). A constraint is called *binding*, if the left-hand side and

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[74] Optimization problems other than linear programming problems have additional requirements for the constraint (in-)equalities to allow for global maximum or minimum solutions. For example, a NLP minimization problem requires convex constraint functions to obtain a unique solution of the problem, cf. e.g. Leonard and Van Long (1992), p. 8ff.

[75] Cf. Winston (2004), p. 52, for definitions of linear functions and linear inequalities.

right-hand side of the (in-) equality assume the same value when the optimal values of the decision variables are applied to the respective constraint. Sign restrictions may apply for each variable, i.e. each decision variable can either be non-negative or unrestricted.

The above formulation of an LP problem contains three implicit assumptions (cf. Winston 2004, p. 53): First, the *proportionality* assumption states that each decision variable x_i contributes in proportion to its value to the overall value of the objective function. The second assumption on *additivity* means that the contribution of one decision variable to the overall objective function is independent of the contribution or values of other decision variables. Third, the *certainty* assumption requires all parameters to be known with certainty.

A formulation of a LP problem frequently required for specific operations[76] is the *standard form* (cf. Cormen, Leiserson et al. 2004, pp. 780ff.). In this form, all constraints are equations and all variables need to be non-negative. To transform inequality constraints into equality constraints, the introduction of *excess* and *slack variables* is required. Excess variables e_i are applied to each ≥ constraint, denoting the amount by which the respective constraint is exceeded. As an example, the LP in equation (6.17) is transformed to

$$\begin{aligned} &\min c^T x \\ &\therefore Ax - e = b \\ &\quad x \geq 0 \\ &\quad e \geq 0 \end{aligned} \tag{6.18}$$

For maximization problems, slack variables s_i are introduced to replace ≤ inequality constraints with equality constraints, with s_i indicating the amount of the resource remaining unutilized in the optimal solution.

For every minimization LP problem, a corresponding maximization LP problem exists which is obtained by transforming the matrix form of the problem, i.e. interchanging rows and columns (cf. equation 6.19). The original LP problem is called the *primal* problem, the transformed LP problem is called the *dual*. The dual of a dual problem is identical to the primal problem.

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[76] E.g. for the simplex algorithm, cf. Dantzig (1949).

$$\begin{aligned} &\max b^T p \\ &\therefore A^T p \le c \\ &\quad p \ge 0 \end{aligned} \tag{6.19}$$

In a dual LP problem, the *i*-th constraint relates to the *i*-th variable x_i of the primal problem. Accordingly, the dual variable p_i is linked to the *i*-th constraint of the primal problem. It follows that the objective function values of both the primal and the dual problem are the same for the optimal solution. This is referred to as the *duality theorem* (cf. Eremin 2002, pp. 61ff., and Winston 2004, pp. 308ff.). Closely related to the dual theorem is the theorem of *complementary slackness* (cf. Winston 2004, p. 326). It stipulates that for a non-binding constraint in the primal LP problem the associated variable in the dual problem must equal zero.

The dual variable p_i is often referred to as *shadow price*, cf. e.g. Winston (2004), p. 313, and Weber (2005b), p. 33. The shadow price of a constraint specifies the change of the optimal value of the objective function if the respective constraint is relaxed by one unit[77]. In other words, for a minimization problem, the shadow price p_i of the *i*-th constraint equals the decrease in the optimal value for the objective function if the right-hand side of constraint *i* is increased from b_i to b_i+1.

6.4.2 Solving deterministic optimization problems

Simple optimization problems with only two variables x_1 and x_2 can be solved graphically by plotting all equations in an x_1-x_2 coordinate system. For more complex problems, algorithms have been developed that allow the manual solution of LP problems. The two most common approaches are probably the *Simplex algorithm*, developed by Dantzig (1949) (cf. e.g. Winston 2004, pp. 210 - 212, and Cormen, Leiserson et al. 2004, pp. 793ff.), and the *Lagrange method*, named after Joseph Lagrange.

The Lagrange method is an algorithm for the solution of NLP problems with equality constraints. Since LP is a special case of NLP, the Lagrange method is suitable for LP problems with equality constraints as well. As it offers some insightful economic interpretations of the equations and results, it is briefly introduced at this point, based on the detailed explanations in Leonard and Van Long (1992).

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[77] With the implicit assumption that after the change of the right-hand side of the constraint the current solution remains optimal, cf. Winston (2004), p. 313.

The objective function $f(x_1,\dots,x_n)$ is minimized for $x_1^*,\dots,x_n^*$, subject to the constraints g^j with $j=1,\dots m$:

$$\begin{aligned} &g^1(x_1,\dots,x_n)=0\\ &\vdots\\ &g^m(x_1,\dots,x_n)=0, \quad m<n \end{aligned} \tag{6.20}$$

By introducing m variables $\lambda_1,\dots,\lambda_m$, the so-called *Lagrange multipliers*, a new function is created. It is referred to as the *Lagrangian function*:

$$L(\lambda_1,\dots,\lambda_m,x_1,\dots,x_n)=f(x_1,\dots,x_n)+\sum_{j=1}^{m}\lambda_j\cdot g^j(x_1,\dots,x_n) \tag{6.21}$$

The point $(\lambda_1^*,\dots,\lambda_m^*,x_1^*,\dots,x_n^*)$ defines the extremum for L. It can be calculated by setting all partial derivatives of L to zero:

$$\begin{aligned} &\frac{\partial L}{\partial \lambda_1}=g^1(\vec{x}^*)=0\\ &\vdots\\ &\frac{\partial L}{\partial \lambda_m}=g^m(\vec{x}^*)=0\\ &\frac{\partial L}{\partial x_1}=f_{x_1}(\vec{x}^*)+\sum_{j=1}^{m}\lambda_j\cdot g^j_{x_1}(\vec{x}^*)=0\\ &\vdots\\ &\frac{\partial L}{\partial x_n}=f_{x_n}(\vec{x}^*)+\sum_{j=1}^{m}\lambda_j\cdot g^j_{x_n}(\vec{x}^*)=0\\ &\text{with } \vec{x}^*=(x_1^*,\dots,x_n^*). \end{aligned} \tag{6.22}$$

A simplified representation of the Lagrange approach helps explaining the concept of shadow prices that play an important role in this thesis. The total costs required to satisfy a given demand X are to be minimized:

$$\begin{aligned} &\min T(x_1,x_2)=c_1F_1(x_1)+c_2F_2(x_2)\\ &\therefore \quad x_1+x_2=X \end{aligned} \tag{6.23}$$

The Lagrangian function can be formulated as

$$L(\lambda,x_1,x_2)=c_1F_1(x_1)+c_2F_2(x_2)+\lambda(X-x_1-x_2) \tag{6.24}$$

with the partial derivatives

$$\begin{aligned} \frac{\partial L}{\partial \lambda} &= X - x_1 - x_2 \\ \frac{\partial L}{\partial x_1} &= c_1 F_1'(x_1) - \lambda \\ \frac{\partial L}{\partial x_2} &= c_2 F_2'(x_2) - \lambda \end{aligned} \tag{6.25}$$

If now the demand *X* is increased by *dX*, the question arises how this additional demand can be satisfied in a cost-minimal way, i.e. what the cost-minimal split between dx_1 and dx_2 is. The cost minimum for the optimal solution T^* changes by

$$dT^* = c_1 F_1'(x_1^*) dx_1 + c_2 F_2'(x_2^*) dx_2 \tag{6.26}$$

For the optimal solution the partial derivatives in equation (6.25) can be set to zero. Thus, equation (6.26) can be written as

$$dT^* = \lambda^* \cdot (dx_1 + dx_2) = \lambda^* \cdot dX \tag{6.27}$$

i.e.

$$\lambda^* = \frac{dT^*}{dX} \tag{6.28}$$

Equation (6.28) shows that the derivative of total minimum costs with respect to demand equals the optimal value of the respective Lagrange multiplier. In other words, an additional demand unit will increase total costs by λ^*. Again, this is the shadow price of the demand (also cf. subsection 6.4.1): “*Thus, the method of Lagrange generates as a by-product of the solution a shadow pricing system that operates as a real one*” (Leonard and Van Long 1992, p. 35). Using this shadow price as the actual price (or cost) results in an optimal x_1^*, x_2^* combination to satisfy the demand at minimum costs. This also referred to as the *invisible hand* or *benevolent dictator* phenomenon, since competitive behavior leads to the same optimal resource allocation that an almighty central planner could achieve.

If also inequalities are allowed as constraints, the Lagrange method is not applicable any more. Instead, the *Kuhn-Tucker conditions* provide a solution to the optimization problem (cf. Leonard and Van Long 1992, pp. 52ff., and Winston 2004, pp. 670ff.). If a minimization problem is given as

$$\begin{aligned}
&\min f(x_1,\ldots,x_n) \\
&\therefore g^1(x_1,\ldots,x_n) \le b_1 \\
&\quad\vdots \\
&\quad g^m(x_1,\ldots,x_n) \le b_m, \quad m < n
\end{aligned} \tag{6.29}$$

with all constraints in "≤" form ("≥" or "=" forms are not allowed) and $\vec{x}^* = (x_1^*,\ldots,x_n^*)$ defining the optimal solution to f, $\vec{x}^*$ must satisfy all constraints in equation (6.29). In addition, a set of Kuhn-Tucker multipliers $\lambda_1^*,\ldots,\lambda_m^*$ must exist that satisfies

$$\begin{aligned}
&\frac{\partial f(\vec{x}^*)}{\partial x_j} + \sum_{i=1}^{m} \lambda_i^* \cdot \frac{\partial g^i(\vec{x}^*)}{\partial x_j} = 0 && \text{for } j = 1,\ldots n \\
&\vec{\lambda}^* \cdot \left[b_i - g^i(\vec{x}^*)\right] = 0 && \text{for } i = 1,\ldots m \\
&\lambda_i^* \ge 0 && \text{for } i = 1,\ldots m
\end{aligned} \tag{6.30}$$

Analogous to the dual LP problem and the Lagrange method, the Kuhn-Tucker multipliers can be considered as shadow prices of the constraints.

In this thesis, the focus is on dynamic discrete-time problems with a finite time horizon $\tau=1,\ldots,T$. For this type of problem, the optimal solution is described by the *Bellman equation*. It postulates that at any period of time *t* the remaining decisions $c^*(t), c^*(t+1), \ldots, c^*(T)$ must be optimal, taking into account the current optimal state of the system $s^*(t)$. $s^*(t)$ depends on the initial state of the system s_1 and all decisions before *t*, i.e. $c^*(1), \ldots, c^*(t-1)$. Formally, the minimization problem based on the objective function ν_τ can be written as (cf. Leonard and Van Long 1992, p. 174):

$$\begin{aligned}
&\min C_t = \sum_{\tau=1}^{T} \nu_\tau(s(\tau), c(\tau)) \\
&\therefore s(\tau+1) = h_\tau(s(\tau), c(\tau)), \qquad \tau = t, t+1,\ldots T \\
&\quad s(\tau) = s^*(t), \\
&\quad s(1) = s_1, \\
&\quad s(T) = \bar{s}
\end{aligned} \tag{6.31}$$

The transition function *h* describes the intertemporal relations of the system states. The initial and terminal values s_1 and $\overline{s}$ are exogenously given. Such a problem can be solved using a backward induction approach (cf. Leonard and Van Long 1992, pp. 176ff.)[78].

6.4.3 Stochastic optimization

So far, all data input for LP problems has been considered as deterministic, i.e. given without any uncertainties. To incorporate uncertainties, stochastic programming is required: "*Stochastic linear programs are linear programs in which some data may be considered uncertain*" (Birge and Louveaux 1997, p. 52). In general, a stochastic problem is described by a set of decisions *x* that have to be made in the absence of perfect information. These decisions are called first-stage decisions. If later some or all of the initially uncertain outcomes or events *ω* have realized, the decision makers may have the opportunity to take corrective actions to adapt to the new situation. These decisions are then called second-stage decisions *y*. The random variables representing the uncertainty of some events are described by probability distributions. In its simplest form[79], a stochastic LP problem can be written as

$$\begin{aligned} &\min\, z = c^T x + E_\xi \left\lfloor \min q(\omega)^T y(\omega) \right\rfloor \\ &\therefore Ax = b \\ &\quad T(\omega)x + Wy(\omega) = h(\omega) \\ &\quad x \geq 0, y(\omega) \geq 0 \end{aligned} \tag{6.32}$$

with *ξ* as the probability distribution of *ω*. *q(ω)*, *h(ω)* and *T(ω)* represent the problem data of the second stage that becomes known when the random event *ω* has realized. *W* is the recourse matrix with *Wy = h-Tx*. For determining the optimal values, the LP can be solved using the Kuhn-Tucker conditions. It is important to note that it is impossible to find a solution that is optimal under all circumstances, i.e. for every possible state. Instead, solving the problem in equation (6.33) yields a solution that is optimal with the highest probability possible.

According to Birge and Louveaux (1997), typical stochastic optimizations problems are characterized by "*many decision variables with many potential values,*

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[78] If the terminal value is only subject to some constraints, e.g. a lower bound, or is not given at all, transversality conditions need to defined to allow for a solution by backward induction. Cf. Leonard and Van Long (1992), p. 176ff., for a description of transversality conditions depending on the type of endpoints constraints.

[79] "*the classical two-stage stochastic linear program with fixed recourse*", cf. Birge and Louveaux (1997), p. 54.

discrete time periods for decisions, the use of expectation functionals for objectives, and known (or partially known) distributions" (p. 67). Wallace and Fleten (2003) point out that while the results of a dynamic deterministic LP problem can be considered as clear-cut optimal decisions, results of stochastic LPs should be rather considered as indications for an optimal strategy or policy. For example, one result from stochastic modeling is presumably a larger share of flexible technologies that would not be part of the optimal solution in a deterministic framework. In particular, Wallace and Fleten refer to the installation of gas combustion turbines in power generation that are only needed if the electricity demand is ex ante unknown and if therefore demand fluctuations require technologies with very short lead times.

If the enumeration of the different possibilities at one decision point is possible, a stochastic LP can be represented by a decision tree (cf. Fig. 6-1). This technique can be used when there are limited numbers of scenarios or decisions per time period that occur with a given probability. If the number of possible decisions per period is large, this type of representation of the problem is not very convenient. The same holds true for a large number of periods in the model. In addition, this is not only a problem of graphical representation but also of computability. If a stochastic LP is implemented in this form, it soon leads to very large problems that may become unsolvable, e.g. due to hardware restrictions. This effect is referred to as the *curse of dimensionality*, since each additional decision alternative greatly increases the number of required mathematical operations[80].

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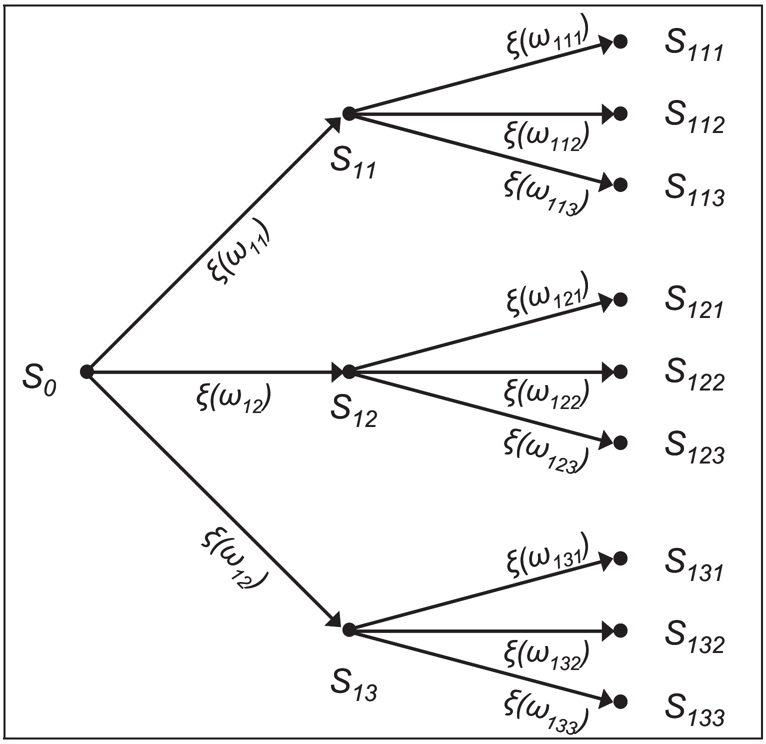
[80] Based on 10 time periods, 4 different possibilities per period lead to 4^{10} = 1,048,576 possible states in the tenth period, compared to 2^{10} = 1,024 or 3^{10} = 59,049 combinations for 2 and 3 possibilities per period.



Source: Own representation

Fig. 6-1: Decision tree (illustrative)

6.4.4 Approximate solutions to stochastic optimization

To reduce the computational complexity of stochastic optimization models, several approaches can be applied, cf. Birge and Louveaux (1997), p. 285ff.

A common approach is the application of the *deterministic equivalent* (cf. subsection 3.2.2.1), reducing the dynamic stochastic optimization problem to a dynamic deterministic optimization problem. This is achieved by replacing the stochastic model parameters with their expected value, based on the underlying probability distribution of the parameters (cf. subsection 6.3.4).

Alternatively, a *three-point discrete-distribution* can be applied (cf. Keefer 1994). Such an approximation consists of three values x_1, x_2 and x_3 with corresponding probabilities of occurrence $p(x_1)$, $p(x_2)$ and $p(x_3)$. The probabilities are chosen to appropriately reflect the probability density function of the random variable X. According to Keefer (1994), the x_i-values are usually specified as quantiles of the cumulative distribution function while the corresponding probabilities $p(x_i)$ are applied based on empirical or theoretical findings.

6.4.5 Repeated deterministic optimization as representation of stochastic shocks

For certain real life business situations, it can be assumed that market participants make their planning decisions based on their expectations driven by the status quo. This means that they usually expect all parameters to remain in the same magnitude as currently given and do not incorporate assumptions about possible future stochastic fluctuations into their decisions. At the next decision point, if some or all of the stochastic inputs have changed, the market participants adapt their plans to the new situation but again consider the new status to remain unchanged in future. Especially for natural resource economics, this behavior is probably not as unrealistic or surprising as it may seem prima facie: "*The reason why pricing of resources might be myopic is that very few planners have the ability, or perhaps even the desire, to check consistency for several decades*" (Nordhaus, Houthakker et al. 1973, p. 536).

To reflect this behavior in economic modeling, a sequence of deterministic optimizations can be applied in which the model inputs change stochastically from one period to the next, e.g. to reflect an unexpected change in available resources. This can be implemented by combining a three-point discrete-distribution as described in subsection 6.4.4 with a Monte-Carlo simulation that is applied to switch between the x_i-values based on the probabilities $p(x_i)$ of the three states for each decision parameter. Thus, a sequence of deterministic optimization models with stochastic replanning can be generated, emulating the random application of shocks to a supposedly deterministic market environment.

As the impact of stochastic shocks on fossil fuels prices is of particular interest in this study, this modeling approach is chosen as the framework for the development of an own model.

6.5 Model risks and validation

Any modeling approach can be subject to errors on various dimensions. This section provides possible types of errors and ways to validate models and their results.

The term *model risk* refers to the risk of the model providing erroneous output values. In literature, three different types of model risks are distinguished, based on the source of error: economic, econometric and technical (cf. e.g. Balci 1994, Barlas 1996, Coyle and Exelby 2000 as well as Roggenstein 2005):

- The *economic model risk* describes risks occurring from the underlying fundamental economic theories of the model. Since a model will never be capable of representing all aspects of the complex reality, simplification and aggregation is required. Using wrong assumptions here leads to misspecification of the economic interrelationships and market behavior, thus potentially resulting in uselessness of the model or at least erroneous output.
- The second type of model risk results from the *econometric estimation* of model parameters. There are three possible sources for econometric model risks: model specification, parameter estimation and verification. *Specification errors* are caused by a deficient numerical or analytical implementation of a correct economic model. For example, an incorrect realization of a cause-and-effect chain through wrong definition of dependent and independent variables falls into this category. *Parameter estimation* has to be carried out when required parameters are not directly observable from the data. Estimation risks can originate from the use of inappropriate estimators or data samples. For example, the usage of a time series of prices for an OLS regression analysis that is not weakly stationary might lead to spurious results regarding the parameter estimation. The third and last source of econometric model risk lies in the *verification of the parameter estimates*. Tests based on null and alternative hypotheses are one possibility to verify a correct parameter estimate. However, since each test is based on model assumptions as well, model risks can never be fully eliminated.
- *Technical model risks* refer to errors in communication between humans, in the human-machine interface or in the hardware-software system of the computer. They range from faulty keyboard entries to computer system crashes.

Model validation should be applied to minimize model risks and to ensure that errors have been eliminated wherever possible. One possible methodology to test and validate a model is to use historic data as input values and to compare the results with observed historic price series. Despite its intuitive appeal, this approach has two major deficiencies. The first is data availability: For all empirical models, the collection and preparation of input data is very time-consuming. As future developments are of large interest in the scientific and general community, a lot of research is devoted to them and data is available to a certain degree. Historical developments in form of detailed time series with a similar degree of details might be much harder to find. The second problem is that, assuming past data has been compiled and fed into the model, the results still give only an indication on model validity but do not definitely prove it: "*It might be very convincing,* […] *if a model reproduces historic data accurately, but it is no proof of the validity of the model. The model might reproduce the data for a completely wrong reason and therefore not be useful in predicting the future*" (Grobbel 1999, p. 18).

Also a deviation from past results does not necessarily indicate a misspecification of the model. In the context of this thesis, chapter 5 has demonstrated the variety of uncertainties impacting fossil fuel prices. A correct reproduction of e.g. historic oil prices requires all uncertainties, e.g. the political events leading to the oil crises in the 1970s, to have the exactly same shape at the same time in the model as they occurred in reality. Neglecting the fact that not all uncertainties have been included in the model, this could be implemented. But since these modifications are obviously not possible and not required for future time periods, the value of such a test remains questionable and is probably not worth the significant effort. Instead, other methods for model validation can be applied as described by Barlas (1996) and Grobbel (1999)[81]:

- *Direct structure tests* are aimed at verifying the model setup by comparing it with observed structures of the real world. Three subcategories can be identified. The first one evaluates the structure of the model by comparing the model equations with interrelations observed in reality. It is therefore called *structure confirmation test*. Barlas (1996) points out that this test is highly qualitative in nature and is hard to formalize and quantify. This type of test can be carried out via interviews and discussions with industry experts. The second category of structure test is termed *parameter confirmation test*. Model parameters, i.e. data input, are checked for consistency with data from actual observations. This can be done both conceptually and numerically. The check for conceptual consistency tries to establish a direct linkage between data observed in real world conditions and parameters employed in a model. A numerical check ensures that model and real world data show the same range of values and dimensions. Another check related to data dimensions is the test for *dimensional consistency*. It ensures that in every equation left-hand side and

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[81] The discussions of the two authors are primarily focused on the validity of system dynamics models. However, due to their general nature, the tests are applicable for optimization models, too.

right-hand side calculations have the same reasonable unit. Another possibility to check model validity is *direct extreme condition* testing. Often, model results in extreme conditions are intuitively clear, e.g. the demand set to zero should result in zero supply. By applying such unrealistic or extreme input data, it can be checked whether the model calculates the expected results or not.

- In the second category which refers to *structure-oriented behavior tests*, again the structure of the model is tested. Two main subcategories can be distinguished: tests for *behavior sensitivity* and for *phase relationship*. The former analysis is performed by identifying the parameters the model is most sensitive to. Results of changes in these parameters are checked against expected outcomes of similar changes in the real world. In the latter type, the interrelations or phases of two or more model variables are checked and compared to real world expectations. For example, if demand goes up, it could be expected that prices rise and/ or supply volumes increase. An inverse relationship, i.e. falling prices and increasing demand, might indicate a model misspecification[82].
- While the two former categories focus on model structures, the third one, called *behavior pattern tests*, is based on model results. Here it is analyzed whether the model results reflect real world patterns or not. Barlas (1996) emphasizes that the reproduction of patterns is the key criterion, not the exact prediction of single data points.

Using the above methods, the integrity and results of the own model can be tested. This approach may lead to better results than backtesting of the model for the reasons explained above.

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[82] In some situations such a development can be appropriate, e.g. when technological advancement or learning curve effects are considered. However, also these effects should be included in the real world expectations the model results are compared with.

6.6 Fossil fuel prices: Review of existing models

At this point, three representative models dedicated to the computation of (fossil) fuels prices are discussed: a cost minimization model by Nordhaus, Houthakker et al. (1973), the LOPEX model from IER, University of Stuttgart, and the POLES model from LEPII at the University of Grenoble[83]. The first one is now nearly 35 years old but still offers some interesting insights as it is a cost minimization approach similar to the techniques that can be applied for an own modeling approach. The two other models are relatively new and thus are good sources for comparison values regarding own calculations.

For the purpose of this thesis, these models are used as references both for modeling techniques, particularly regarding the underlying major assumptions, as well as for results. In this section, methodologies and individual results are presented and discussed. A comparison with the own results will take place once an own model has been developed and described, i.e. at the end of chapter 7.

6.6.1 Cost minimization model by Nordhaus, Houthakker et. al.

The objective of the model is to minimize the costs related to the satisfaction of an exogenously given inelastic energy demand. It covers the entire non-Communist world, broken down into five regions. Since the authors consider an optimization period of fifty years as too myopic, the period under consideration is extended to 200 years, split into five 10-year periods, two 25-year periods and two 50-year periods.

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[83] Many other models are skipped here for the sake of conciseness. Bergman (1988) provides an overview on some general equilibrium models in his publication on energy policy modeling. One particular modeling approach that will not be further dealt with here is the IIASA group of models described in Nakicenovic, Gruebler et al. (1998). This is due to the complexity of the approach since the data is generated by at least seven different models, various databases and sophisticated linking methodologies between the models. Cf. Nakicenovic, Gruebler et al. (1998), p. 256, for a graphic representation of the model interrelations. Furthermore, fuel prices are not the prime purpose of this study but only one (minor) result among a large set of social, economic and technical indicators. Consequently, prices are only displayed as index, limiting the comparability with results from other models.
Two models from the EIA are worth mentioning: First, the SAGE model (System for the Analysis of Global Energy Markets, cf. OIAF/ EIA 2003a, 2003b) is an "*integrated set of regional models that provides a technology-rich basis for estimating regional energy supply and demand*" (OIAF/ EIA 2003a, p.6). The International Energy Outlook reports, e.g. EIA/ DOE (2006), are based on calculations of the SAGE model. An overview on the SAGE model structure and results can be found in Tab. 5-1 and Tab. 5-2 of this thesis. The second EIA model is called NEMS (National Energy Model System, cf. OIAF/ EIA 2003c). As the focus of NEMS is limited to the energy markets in the U.S.A. only, its results are only of little value for the purpose of this thesis, where the global fuel markets are in scope, with a particular emphasis on the development in Western Europe. However, NEMS is an example for a very sophisticated model with a complex structure, including a dedicated module for each demand segment and fuel type.

Starting point is the year 1970. In principle, even this 200-year optimization period is considered as too short by the authors since "*the planning period for essential exhaustible resources must cover the duration of man's habitation on the planet*" (Nordhaus, Houthakker et al. 1973, p. 547). To correct this flaw, a high-cost backstop technology with an unlimited resource base (breeder reactors) is introduced[84].

Energy demand is broken down into five sectors and can be satisfied with four different primary fuel types: crude oil, natural gas, coal and uranium. Solar energy and biofuels are excluded because they are not assumed to ever become economically viable.

For the period from 1970 until 2000, the model predicts the usage of crude oil and natural gas being the sole energy sources for all purposes. Only after the turn of the millennium, the deployment of light-water reactors for power generation is forecasted. In the same way, also coal reserves remain unused until 2000 when they are forecasted to be used for industrial heat and coal liquefaction. From 2020, all energy conversion processes worldwide – with the exception of power generation – are forecasted to be fueled by raw or processed coal and shale oil, with the U.S.A. being the most important supplier of these fuels to the world markets. By 2120, all fossil fuels are exhausted and all energy demand is satisfied by breeder technologies (cf. Nordhaus, Houthakker et al. 1973, p. 552).

in US-$$_{1970}$	**Natural gas (cents p. 1000 cf, average at wellhead)**	**Bituminous coal and lignite (f.o.b. at mine, average dollar per ton)**	**Crude oil (per barrel)**
1970	21.0	11.91	1.20
1980	37.6	12.07	1.70
1990	45.7	12.42	2.13
2000	64.1	13.34	3.19
2010	97.1	15.77	7.12

Source: Own representation based on
Nordhaus, Houthakker et al. (1973), p. 555f.

Tab. 6-2: Results from Nordhaus model

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[84] "*Resources for automobiles operating on electricity generated by breeder reactors will last approximately 100 million years*", Nordhaus, Houthakker et al. (1973), p. 548.

The fuel prices delivered from the model are composed of the shadow prices of the optimization which equal the royalty or scarcity rent of the fuels plus extraction costs which are not included in the shadow prices. Tab. 6-2 shows the results of the model in US-$_{1970}$.

For crude oil, the authors notice that pre-oil crisis market prices include a markup of about 170 percent compared to the prices calculated in their model – i.e. 3.23 US-$/bbl observed market price in 1970 compared to 1.20 US-$/bbl as calculated price. They attribute this difference partly to crude oil import quotas for the U.S. but primarily to excess royalties for the fuel producers due to the realization of cartel rent as well as an incorrect assessment of scarcity.

6.6.2 Long-term Price and Extraction (LOPEX) model

The optimization model LOPEX, described in Rehrl and Friedrich (2006), was developed by the Institute of Energy Economics and the Rational Use of Energy (IER) at the University of Stuttgart, Germany. It covers the global fossil fuel supply in the entire 21st century, split into 10-year periods. LOPEX can run in an iterative combination with NEWAGE[85], a general equilibrium model determining the global demand for fossil fuels.

There are separate model modules for each fossil fuel, named LOPEX-oil, LOPEX-gas and LOPEX-coal, respectively. All modules approach the problem from a supply-oriented perspective, assuming that all suppliers of fossil fuels seek an intertemporally optimal production of their stocks. The optimal decisions for all periods are calculated in a synchronous computation. Remaining volumes at the end of the optimization period in 2100 are considered worthless, which leads to a certain distortion of results in the later periods.

The global demand is initially given by a reference price-demand relation. However, defined elasticities provide the possibility for demand adaptations to price developments and thus allow for an endogenous calculation of prices, supply and demand. Results from the EU project SAUNER[86] are used as input data for resource availability and costs. Cost data is primarily related to production and transportation.

The split into three model modules is made to reflect the specific market situation for crude oil. The oil model only distinguishes between OPEC and Non-OPEC

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[85] National, European, World-wide Applied General Equilibrium Modeling System, cf. Böhringer (1999)

[86] Sustainability And the Use of Non-rEnewable Resources, cf. Markandya, Mason et al. (2000)

countries, whereas the natural gas and coal models divide the world into 12 regions for supply and demand. The split into OPEC and Non-OPEC countries permits the modeling of a cartel with a competitive fringe for the oil market. In LOPEX-oil, Hubbert curves are employed to describe the output characteristics of Non-OPEC countries, whereas OPEC production is instead limited by exploration and development activities and is not bound by Hubbert-type restrictions. For natural gas and coal, production capacities with given maximum extension or downsizing limits describe the possible production.

A reference scenario is calculated for each fossil fuel which can then be altered by varying different model parameters, e.g. interest rate, demand elasticity or OPEC market share. Below are the results from the three reference cases after seven iterations between LOPEX and NEWAGE, shown in US-$\$_{1998}$/boe.

in US-$\$_{1999}$/boe		**Iteration**	**2000**	**2010**	**2020**	**2030**
Crude oil	**NEWAGE**	**Baseline**	26.77	27.48	24.58	26.56
	LOPEX	**1**	24.11	31.90	44.64	62.58
	NEWAGE	**7**	19.61	27.48	43.99	61.40
	LOPEX	**7**	19.43	26.69	44.98	63.85
Natural gas	**NEWAGE**	**Baseline**	22.77	22.40	21.76	23.28
	LOPEX	**1**	10.80	15.78	17.50	20.07
	NEWAGE	**7**	12.13	12.83	16.98	19.60
	LOPEX	**7**	10.30	14.98	18.96	21.57
Coal	**NEWAGE**	**Baseline**	15.79	17.49	17.93	19.95
	LOPEX	**1**	6.19	7.27	8.55	10.38
	NEWAGE	**7**	8.25	8.06	10.77	13.76
	LOPEX	**7**	6.21	8.38	10.59	13.41

Source: Own representation based on
Rehrl and Friedrich (2006) and
Fahl, Bickel et al. (2004), p. 72

Tab. 6-3: LOPEX/ NEWAGE results

6.6.3 Prospective Outlook on Long-term Energy Strategy (POLES) model

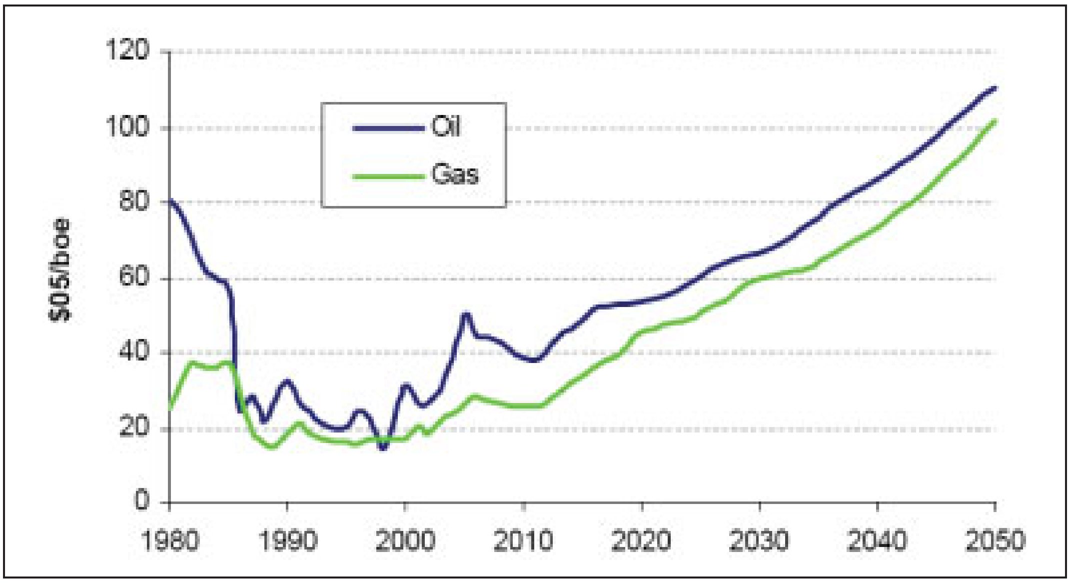
POLES is a dynamic partial equilibrium model, developed by the LEPII institute (formerly known as IEPE) at the University of Grenoble, France. It is fully operational since 1997, and its version “POLES 5” is described in LEPII-EPE (2006a), (2006b). It is a simulation model that focuses on the electricity sector (12 available generation technologies and 12 further new technologies not in usage yet) and the related greenhouse gas emissions. In a year-by-year recursive approach, it covers the years 2005 to 2050.

POLES 5 is composed of 46 regions in the world with 22 energy demand sectors and about 40 energy technologies, including carbon capture and sequestration as well as hydrogen technologies. Endogenous technology improvements are described by two-factor learning curves, thus incorporating experiences from technology application as well as improvements from research activities. The provision of niche markets allows for a smooth diffusion of new technologies into the market. Especially in the power sector, POLES applies a putty-clay approach (cf. Johansen 1959) for the simulation of capacity developments, assuming that both earlier investment decisions and expectation of future price trends determine the current generation portfolio and investment choices.

Input data into POLES includes macro-economic data like population, GDP, characteristics of economic structures and exchange rates as well as technical data like existing equipment characteristics and technology costs.

For fossil fuels, each fuel type is implemented differently. There is one world market for crude oil with the oil price being determined by the capacity utilization ratio of the Persian Gulf countries as short-term driver and the global reserve-to-production ratio as the long-term driver. The investment in oil production capacities is simulated based on a model of the exploration and development process with the degree of the URR depletion in combination with the extent of drilling activities as key indicators. The natural gas and coal markets are however split into three regions (Americas, Europe and Asia), with the regional prices depending on the regional reserve-to-production ratio for gas or respectively on the regional coal production capacities as well as regional import and export restrictions. For natural gas, volume flows are also modeled based on bilateral trades.

Also taking into account transportation costs and CO_2 emissions costs from an endogenous emission quotas trading model, POLES yields data on regional trends for energy supply, demand and prices until 2050 as well as marginal CO_2 abatement costs by region and sector. POLES is often used for reports published by the European Union, e.g. the WETO report (cf. EU 2003a). Fig. 6-2 shows the results for the projections of the oil and gas prices in the Reference Case (in US-$\$_{2005}$/boe).

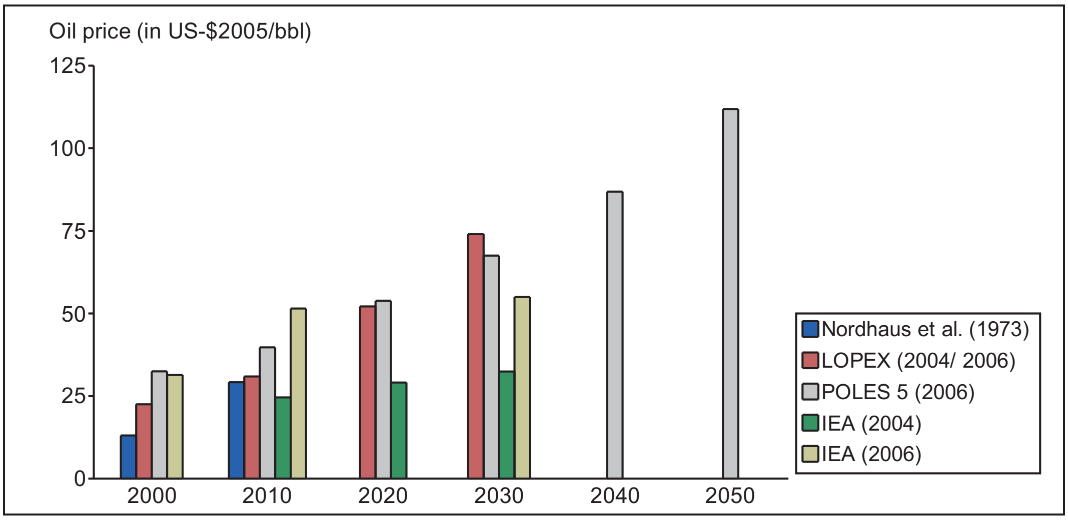


Source: LEPII-EPE (2006b), p. 21

Fig. 6-2: POLES 5 results for oil and gas (Reference Case)

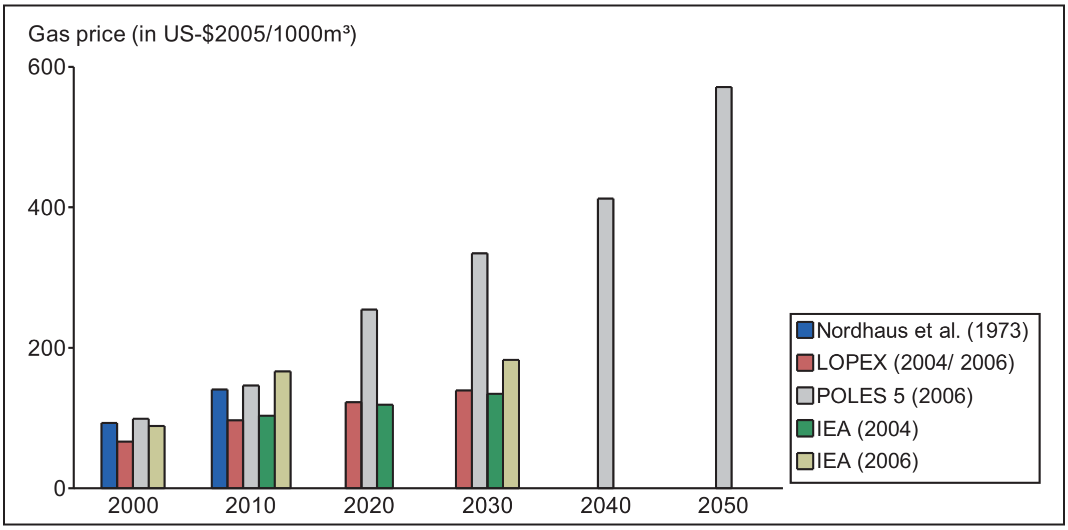
6.6.4 Comparison of model results

To allow for a meaningful comparison of the model results, Fig. 6-3 and Fig. 6-4 show a summary for oil and gas. Estimates from IEA (2004), (2006) have been added to provide additional insights. Actual prices for the year 2000 can also be taken from the IEA (2006) numbers. All prices have been converted to US-$_{2005}$ prices per bbl or 1000 Nm³, respectively.



Source: Own representation based on Nordhaus, Houthakker et al. (1973),
Fahl, Bickel et al. (2004), Rehrl and Friedrich (2006),
LEPII-EPE (2006b) and IEA (2004), (2006)

Fig. 6-3: Overview on model results for oil prices



Source: Own representation based on Nordhaus, Houthakker et al. (1973), Fahl, Bickel et al. (2004), Rehrl and Friedrich (2006), LEPII-EPE (2006b) and IEA (2004), (2006)

Fig. 6-4: Overview on model results for gas prices

Results from Nordhaus, Houthakker et al. (1973) have rather an anecdotic value because of their age and the range of forecast being limited to 2010. When comparing results from the POLES and LOPEX models, it occurs that while results for crude oil prices are about the same magnitude, especially in the years 2020 and 2030, the results for natural gas prices differ significantly. In 2020, the POLES forecast is about double the value from the LOPEX forecast. It occurs that in POLES, the gas price follows the oil price very closely (cf. Fig. 6-2), whereas in LOPEX the prices between oil and gas expressed in US-$/boe are allowed to differ widely (cf. Tab. 6-3). Here, the gap even increases over time. While the ratio of gas to oil price is about 56 percent in 2010, it decreases to 33 percent in 2030. The reason for these differences is of course hard to tell without having access to the exact model specifications and inputs. One possibility is the usage of the SAUNER data by Markandya, Mason et al. (2000) as basis for the reserves and resources assessment in LOPEX. The SAUNER data is based on rather optimistic data regarding available fuel deposits which might lead to an understatement of production costs. However, this still does not explain why the differences only occur for natural gas, and not for crude oil. Obviously, the price for natural gas in POLES is much tighter linked to the oil price than in LOPEX.

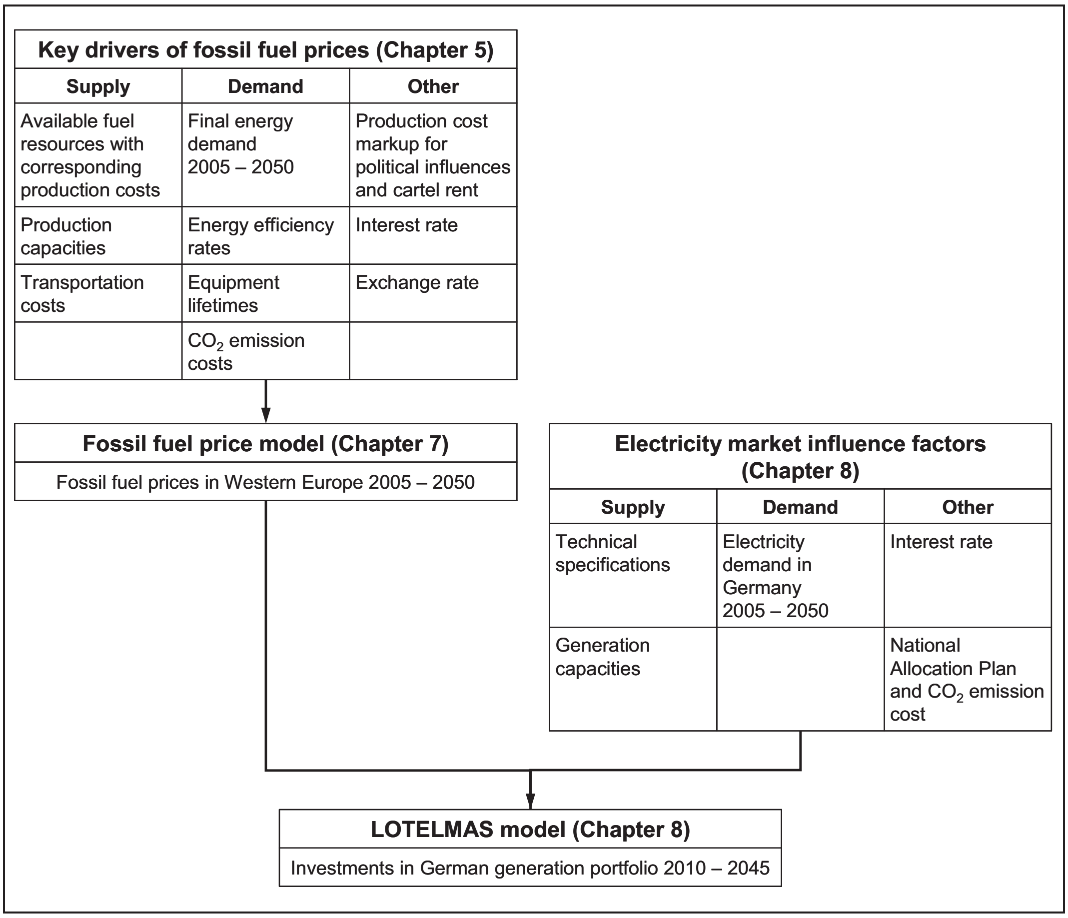
Especially the POLES model is used for calculations by high-level publications (e.g. cf. EU 2003a). Thus, POLES results can be considered as a reliable source for reference values for the own calculations. Of course, depending on the underlying assumptions, results between the various models can differ considerably. Still, at least the magnitude of results and probably also the percental change of prices should show some similarities. A comparison of the own results with results from the models introduced here will be carried out at the end of the chapter once an own model has been implemented.

7 DEVELOPMENT OF A MODEL FOR DERIVATION OF LONG-TERM PRICE SERIES FOR FOSSIL FUELS

In this chapter, based on the previous analyses, an own empirical model is developed and its results are discussed, also in relation to results obtained with corresponding models (cf. section 6.6). The main pragmatic objective is to provide a corridor of possible fossil fuel prices until 2050. For each of the four fossil fuels under consideration, the model should yield a probability range of prices on a 5-year basis. Calculations are carried out both deterministically and stochastically. The outcome from the deterministic calculation is primarily used as reference case to interpret the stochastic results. The deterministic results should thus be considered only in this context, not as a stand-alone prediction.

The ability to calculate a probability-weighted range of prices is gained by implementing the most relevant key drivers and their related uncertainties as stochastic input parameters in a linear optimization framework. Still, as not all parameters are implemented stochastically, the projections shown in this chapter should be regarded as lower bounds to prices based on fundamental data like production and transportation costs. Key drivers on prices that are not included in the model, especially those related to (geo-)political events, can easily lead to significant deviations from the forecasts presented here. However, the structure of the model both allows for the addition of further stochastic parameters as well as for the modification of the existing stochastic parameters, if the underlying assumptions change.

With regard to regional scope, it needs to be emphasized that the model can deliver the same set of results for each of the considered regions. For this thesis, the results shown and discussed are limited to Western Europe. This is due to the proposed application of the results in a model of the German electricity industry (cf. chapter 8) for which the European prices – after adjusting for additional regional distribution costs – are used as input data. This is illustrated in Fig. 7-1: The model developed in this chapter is based on a selection of the most relevant input data from chapter 5. From the model results, the price series for Western Europe are used together with additional data as input for the LOTELMAS model in chapter 8. However, many other applications of the projections from this model are conceivable.



Key drivers of fossil fuel prices (Chapter 5)

Supply	Demand	Other
Available fuel resources with corresponding production costs	Final energy demand 2005 – 2050	Production cost markup for political influences and cartel rent
Production capacities	Energy efficiency rates	Interest rate
Transportation costs	Equipment lifetimes	Exchange rate
	CO_2 emission costs	

Fossil fuel price model (Chapter 7)

Fossil fuel prices in Western Europe 2005 – 2050

Electricity market influence factors (Chapter 8)

Supply	Demand	Other
Technical specifications	Electricity demand in Germany 2005 – 2050	Interest rate
Generation capacities		National Allocation Plan and CO_2 emission cost

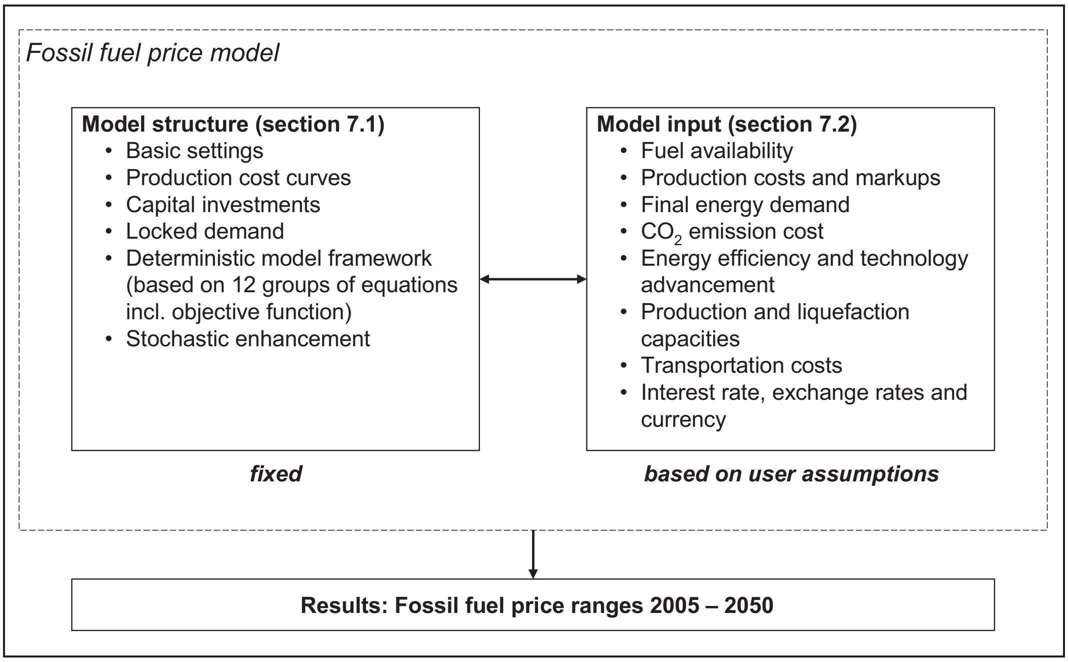
LOTELMAS model (Chapter 8)

Investments in German generation portfolio 2010 – 2045

Source: Own representation

Fig. 7-1: Model data flow in chapters 7 and 8

For the model, two major parts have to be distinguished: On the one hand, there is the *model structure*, basically consisting of a LP model with a cost-minimizing objective function and additional constraints, clustered into 12 groups of equations. On the other hand, there is the *model input*, including all data required to run the model. Key components are four stochastic input parameters describing fundamental uncertainties. Furthermore, there are numerous deterministic input parameters. To yield results, both model components are required. An overview is shown in Fig. 7-2.



Source: Own representation

Fig. 7-2: Overview of fossil fuel price model

The model structure is discussed in section 7.1. In a first step, the basic settings, e.g. the global regions, fossil fuel types and demand sectors considered in the model, are defined. Important model features, i.e. the way of implementing production costs, capital investments and the concept of locked demand, are discussed subsequently. Following that, the model equations are derived in a deterministic framework, including the objective function and all model constraints.

For the stochastic enhancement, the model follows a successive two-step approach. In a first step, the expected development is calculated in an intertemporal deterministic optimization. In the second step, stochastic shocks are applied based on the approach outlined in subsection 6.4.4 and restricted optimizations are carried out.

The model input is then addressed in section 7.2. The most relevant input data comprises information regarding fuel volumes and corresponding production cost data, final energy demand, CO_2 emission costs, energy efficiency rates, capacities for fuel production and liquefaction, transportation costs as well as some financial data like interest and exchange rates.

The discussion and analysis of results takes place in the third and fourth section. Finally, implications are reviewed in the fifth section.

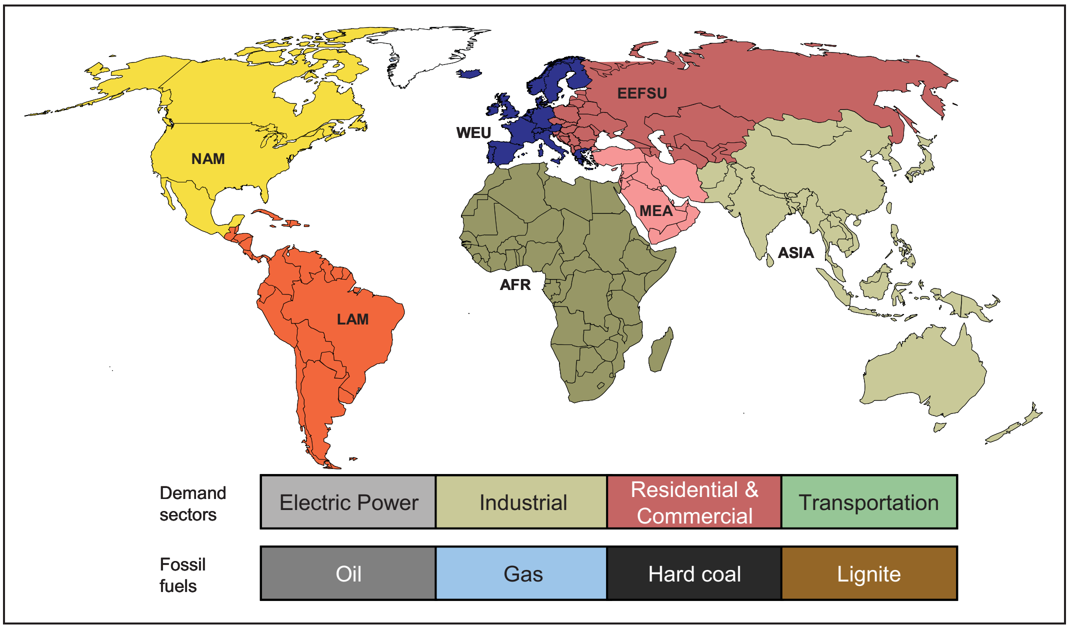
7.1 Model structure

7.1.1 Basic settings

To allow for meaningful results for fossil fuel prices in Western Europe, a comprehensive, global approach is required. Thus, the model incorporates the energy supply and demand in seven geographic regions, covering the entire globe: *North America*, *Latin America*, *Western Europe*, *Africa*, *Eastern Europe & Former Soviet Union*, *Middle East* and *Asia*.

Even though a more detailed breakdown would have been preferable in some cases (especially for *Asia*), the limitation of regions is a tradeoff between desired accuracy of the results on the one hand and available modeling resources, i.e. accessible input data and computer hardware restrictions, on the other hand.

On the supply side, the four major fossil fuels are included in the model, i.e. *Hard Coal*, *Oil*, *Lignite* and *Natural Gas*. Renewable, nuclear and other fuels are not included due to the focus on fossil fuels. Of course there are interdependencies between fossil and non-fossil fuels but they have not been modeled explicitly yet. Instead, the energy demand data is limited to the share of the total demand that is forecasted to be satisfied by fossil fuels, adjusted by a price elasticity of the demand. This demand elasticity is assumed to reflect both substitution effects with non-fossil fuels and capital as well as general demand reductions (cf. subsection 5.2.3). The demand forecasts are based on IEA (2004) and are broken down into four demand sectors: *Electric Power*, *Industrial*, *Residential & Commercial* as well as *Transportation*. The *Transportation* sector again falls into the two subsectors *Passengers* and *Freight*. An overview on these model components is depicted in Fig. 7-3. The demand side of the model consists of the final energy demand and data on the energy conversion efficiency rates of each sector in each region.



Source: Own representation

Fig. 7-3: Overview on model components

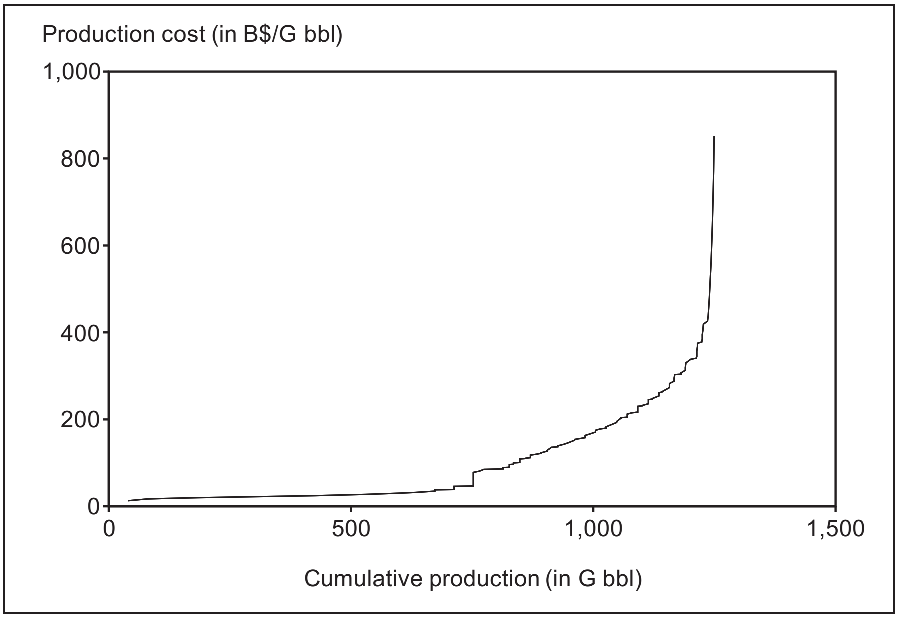
The calculation period ranges from 2005 until 2050 to allow for the long-time planning horizons in the power generation industry. Since the long-term development is of greater interest than negligible short-term price spikes, the results are calculated every five years. The year 2005 serves as initialization point for the model, i.e. parameters that can vary in subsequent model periods are set to a fixed value, reflecting the actual situation in 2005.

7.1.2 Production cost curves

For energy commodities, it is postulated in literature that production costs are the key component of a long-term price path to which short-term time series of prices exhibit mean-reversion: "*Prices gravitate to the cost of production*" (Clewlow and Strickland 2000, p. 39). As short-term deviations are not considered here, production costs are a key element of price calculation in this model.

One of the key drivers of production costs and also scarcity rent is fuel availability. Chapter 4 shows that the global availability of the various fossil fuels over a longer time span has been subject of heated discussions for several decades. For this thesis, it is assumed that production costs increase gradually with cumulative production. Another important assumption made is that resources are depleted according to their production costs, i.e. that cheapest resources are extracted first. From these two assumptions, it follows that for each fossil fuel and each region, the resource is available in a step-wise series of grades. Each step or grade indicates the volume that can be produced at a given cost level[87]. The available amounts of fuels are chosen in a way that they can be considered to be unlimited for the period under consideration[88].

Such a production cost curve exists for each fuel type in each region. In addition, for crude oil and natural gas, there are three scenarios of fuel availability for the stochastic implementation (*LOW*, *MID* and *HIGH* cases, see subsection 7.1.6), adding up to 56 cost curves in total. Each cost curve consists of 178 steps with different step widths. The step width indicates the volume of a fuel available for production at a given extraction cost and differs from step to step, from fuel to fuel and from region to region. Fig. 7-4 shows an exemplary production cost curve (Middle East crude oil for the *MID* case). All cost data employed in the model is shown in US-$\$_{2005}$.



Source: Own representation based on Markandya, Mason et al. (2000), updated with data from BGR (2003), (2004)

Fig. 7-4: Production cost curve (Oil, Middle East, MID case)

Following Masseron (1990), total expenditures of fuel production are to be split up into exploration, development and extraction expenditures. In this model, ex-

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[87] Such a continuum is called „Ricardian”, in reference to David Ricardo. Cf. Ricardo (1821), chapter 2.

[88] Due to the discrete-numerical nature of the linear optimization model, meaning that all input data has to be provided as numbers, the total amounts of fuels are in fact not unlimited. However, they have been chosen so large that global fuel availability does not become a binding constraint in the model. Still, each extracted unit results in an increased effort to extract the next unit.

ploration and development expenditures are considered as fixed costs that apply regardless of the current capacity utilization. Extraction expenditures occur only if the production facility is utilized in the considered period. For crude oil, Masseron estimated that exploration costs account for 10 to 20 percent, development costs for 40 to 60 percent and extraction costs for 20 to 50 percent of total oil production expenditures (Masseron 1990, pp. 97f.).

From the accessible data sources, the total production costs are only available as a total figure in US-$\$_{2005}$ per Gt or Gm³. To allow for a split into fixed and variable costs, it is assumed that variable costs account for 40 percent for oil and gas, for 70 percent for hard coal and for 80 percent for lignite, based on the above assessment from Masseron (1990).

7.1.3 Capital investments

The model applies the putty-clay approach that was introduced by Johansen (1959) to reflect the dynamics of capital investments[89]. In a putty-clay approach, once a capital investment is made, it operates through its entire life span, requiring a predetermined amount and type of input. There are no possibilities for substitution with other inputs until the end of the life span has been reached and a new investment is made: "*The putty-clay model delivers a low elasticity of energy use in the short run, because existing capital uses energy in fixed proportions. In the long run, in response to permanent differences in energy prices, agents invest in different capital goods with different fixed energy intensities. As a result, in the long run, energy use is responsive to differences in energy prices*" (Atkeson and Kehoe 1999, p. 1028).

For the model developed here, this describes how investments on the demand side create a demand for a specific fossil fuel that cannot be satisfied by a different fuel.

7.1.4 Locked demand

If fuel switching were easily possible with given supply and conversion technologies, the impact of stochastic fuel price fluctuations would be substantially lessened. Yet this is obviously not the case, since power plants, car engines and other technologies usually can hardly shift to alternative fuels. Following the putty-clay approach, the concept of *locked demand* is introduced in the model. It

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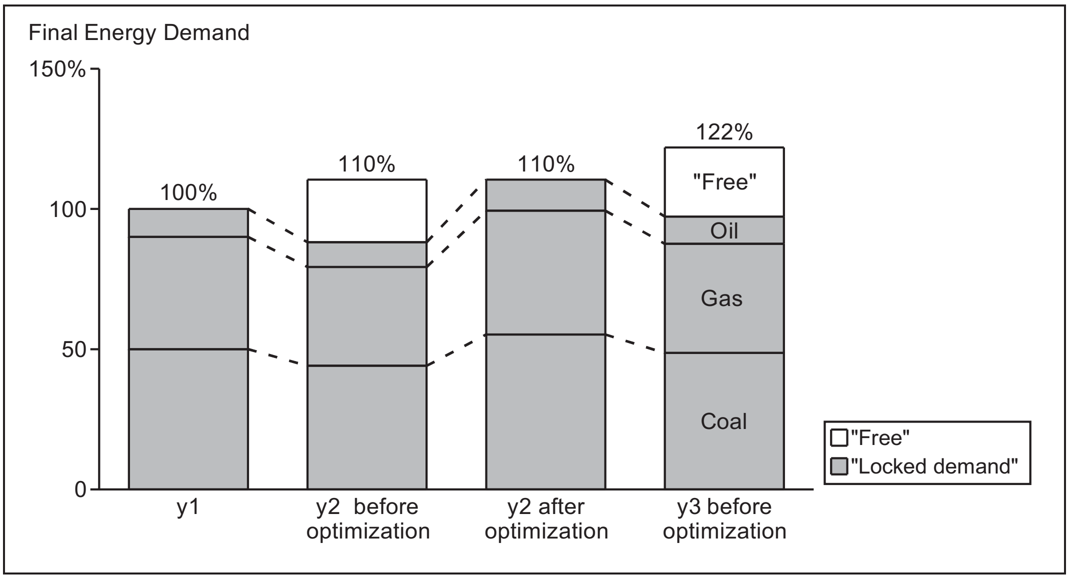
[89] For further discussions of putty-clay modeling techniques also cf. Gilchrist and Williams (2000), (2005).

characterizes the share of final energy demand that cannot be satisfied with one fossil fuel in one period and with a different fuel in the next period. Thus, once an investment in a demand sector facility has been made, the demand satisfied by this investment is considered as locked and requires the same fossil fuel throughout the entire lifetime of the investment. Having reached the end of their lifetime, the demand-side investments are not available any longer (*sudden decay assumption*) and a new investment and thus a new fuel type decision can be made.

This concept is illustrated in Fig. 7-5. In the first period *y1*, the final energy demand is satisfied by a mixture of fossil fuels depending on the installed demand-side technologies. Of these technologies, a certain share (about 12 percent in this example) reaches the end of its lifetime until period *y2*. In addition, an increase in total demand occurs from 100 percent in *y1* to 110 percent in *y2*. As a result, about 22 percent (in relation to *y1*) of the final energy demand can be satisfied without the need to consider fuel constraints from existing technologies (white boxes in Fig. 7-5). The major share of about 88 percent, i.e. the grey boxes in Fig. 7-5, is still bound to one specific fuel determined by the demand-side investments from previous periods. This share is not available for an unconstrained optimization (in terms of choice of fuel).

Existing demand-side investments in 2005 have been assigned a shorter residual lifetime to reflect investment dates prior to the modeled time span.



Source: Own representation

Fig. 7-5: Illustration of *locked demand* principle

7.1.5 Deterministic model framework

The model is implemented using the modeling and optimization software GAMS (cf. GAMS Development Corporation 2006). In the first calculation step, the expected resource extraction and price development is computed in a deterministic intertemporal optimization. This means all optimization periods are considered simultaneously and stochastic fluctuations are replaced by their expected values. The results are then determined by the restrictions and objective function described in the following. To facilitate understanding, the individual equations have been arranged into 12 groups, based on their purpose in the model. Both the model description below and the source code of the model follow this categorization. Tab. 7-1 provides an overview on the equation groups[90]:

Equation group	Denotation	Purpose
I	Final energy demand	• Satisfy given final energy demand • Allow demand elasticity
II	Locked demand	• Ensure consideration of locked demand • Calculate locked demand
III	Total cumulative production	• Limit production to available fuel volumes • Calculate cumulative production in each period
IV	Production capacities	• Limit production to available capacities • Define admissible capacity investments and divestments
V	Capacity investment and divestment costs	• Calculate costs for capacity investments and divestments
VI	Coal and gas liquefaction	• Define ratios and costs for liquefaction processes • Limit liquefaction to available capacities • Define admissible capacity investments and calculate investment costs
VII	Maximum fuel shares	• Define maximum fuel shares for particular fuels and demand sectors
VIII	Mapping of production volumes and capacities to production cost curve	• Map fuel volumes and capacities to production cost curves
IX	Fixed and variable production costs	• Calculate fixed and variable costs of production • Calculate residual value of remaining fuel volumes beyond model horizon
X	Transportation costs	• Calculate transportation costs
XI	CO_2 emission costs	• Calculate CO_2 emission costs from combustion and liquefaction processes
XII	Objective function	• Discount costs from all periods to 2005 • Add up all cost types for optimization

Source: Own representation

Tab. 7-1: Overview on model equations

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[90] For the *Transportation* sector, some of the restrictions are formulated slightly differently to allow for the two subsectors and different measures of energy conversion efficiency. These equations are not detailed in the following to avoid overwhelming details.

The indices used in the model can be found in Tab. 7-2.

ds	demand sector
f	fossil fuel type
ft	fuel type (fossil vs. non-fossil)
fy	fixed year (e.g. year of investment)
i_cap	capacity utilization step
i_demred	demand reduction step
r	region of fuel production
rr	region of fuel consumption
st	production cost curve step
tr_type	transportation type for fuel shipments
tt	transportation subsector
y	year

Source: Own representation

Tab. 7-2: Indices overview

The calculations of the deterministic optimization should be regarded as reference scenario for the stochastic calculations. The deterministic version has also been used to provide starting values for the stochastic optimization (e.g. for demand reduction costs, see below).

I. Final energy demand

Fuel volumes in a region available for consumption ($vol\_rregion_{ds,f,rr,y}$) result from fuel volumes from regular production ($vol_{ds,r,f,rr,y}$) plus oil from coal liquefaction ($vol\_ctl_{ds,f=OIL,rr,y}$) as well as oil from gas liquefaction ($vol\_gtl_{ds,r,f=OIL,rr,y}$), cf. constraint (7.1). It is assumed that coal liquefaction takes place in the regions where the oil is consumed whereas gas liquefaction occurs in the regions of gas production, which explains the different indices of the variables.

$$\sum_r vol_{ds,r,f,rr,y} + vol\_ctl_{ds,f=OIL,rr,y} + \sum_r vol\_gtl_{ds,r,f,rr,y} = vol\_rregion_{ds,f,rr,y} \qquad (7.1)$$

The sum of fossil fuels in a region multiplied by the fuel-specific energy density en_den_f and energy conversion efficiency rate $eff_{ds,rr,f,y}$ must be equal to or greater than the corresponding final energy demand $fin\_dem_{ds,rr,ft,y}$. To include elasticity of the demand, final energy demand can be reduced in four steps called $demred_{i\_demred,ds,rr,y}$:

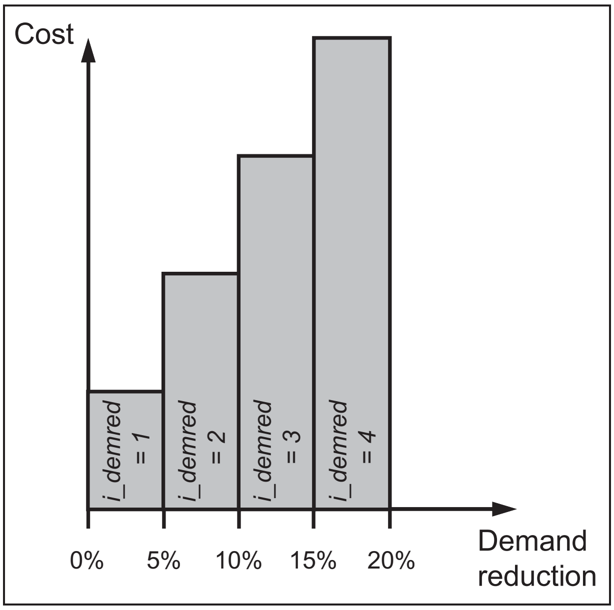
$$\begin{aligned}&\sum_{f} vol\_rregion_{ds,f,rr,y} \cdot en\_den_{f} \cdot eff_{ds,rr,f,y}\\ &\geq fin\_dem_{ds,rr,ft='FOSSIL',y} \cdot (1 - \sum_{i\_demred} demred_{i\_demred,ds,rr,y})\end{aligned} \tag{7.2}$$

Each step of demand reduction must not exceed a given maximum *demred_max*$_{i\_demred,ds,rr}$, which has been set to five percent:

$$demred_{i\_demred,ds,rr,y} \leq demred\_max_{i\_demred,ds,rr} \tag{7.3}$$

The reduction of total demand causes (opportunity) costs *demred_cost*$_{ds,rr,y}$ in the region, e.g. through foregone profits or higher capital investments for efficiency improvements. These costs are not incorporated into the fuel costs shown in section 7.3 below but add to the objective function of the optimization problem. The calculation of the costs in constraint (7.4) rests upon a base cost per unit of reduced demand (*demred_uc*$_{ds,rr,y}$), multiplied with a markup *demred_cost_mult*$_{i\_demred,ds,rr}$. The level of the markup depends on the reduction step *i_demred*. This means that the higher the cumulative reduction, the higher the incurred costs (cf. Fig. 7-6).

$$\begin{aligned}demred\_cost_{ds,rr,y} = &\sum_{i\_demred} (fin\_dem_{ds,rr,ft='FOSSIL',y} \cdot demred_{i\_demred,ds,rr,y})\\ &\cdot demred\_uc_{ds,rr,y} \cdot demred\_cost\_mult_{i\_demred,ds,rr}\end{aligned} \tag{7.4}$$



Source: Own representation

Fig. 7-6: Schematic curve of demand reduction costs

The estimation of the costs for demand reduction is based on the assumption of a long-term elasticity of the demand of 0.1 (cf. subsection 5.2.3) and has been calibrated in a way that only minor reductions occur in the deterministic reference scenario.

II. Locked demand

In order to account for poor fuel flexibility of existing plants and facilities, the sum of fossil fuel volumes from regular production and oil from coal or gas liquefaction multiplied by fuel-specific energy density and energy conversion efficiency must be equal to or greater than the so-called locked demand $lock\_dem_{ds,f,rr,y}$. This is the demand covered by investments in earlier periods that require a certain fuel type. To provide some flexibility, e.g. to reflect decisions on the demand side to switch to a technology requiring a different fuel before the lifetime of the existing technology has expired, only 80 percent of the locked demand need to be satisfied (cf. constraint 7.5).

$$vol\_rregion_{ds,f,rr,y} \cdot en\_den_{f} \cdot eff_{ds,f,rr,y} \geq 0.8 \cdot lock\_dem_{ds,f,rr,y} \tag{7.5}$$

Locked demand is calculated as sum of residual locked demand volumes $lock\_dem\_save_{ds,f,rr,y,fy}$ from current and previous periods:

$$lock\_dem_{ds,f,rr,y} = \sum_{fy}^{fy \leq y} lock\_dem\_save_{ds,f,rr,y,fy} \tag{7.6}$$

To calculate the residual locked demand, the new locked demand $lock\_dem\_new_{ds,f,rr,y}$ needs to be calculated first. New locked demand of a given period results from the total final energy provided for a demand sector in a specific region in the previous period less the locked demand in that demand sector and region in the previous period, as shown in constraint (7.7). In other words, new locked demand equals the amount of final energy exceeding the amount required to satisfy the existing locked demand.

$$\begin{aligned} lock\_dem\_new_{ds,f,rr,y} = {} & vol\_rregion_{ds,f,rr,y-1} \cdot en\_den_{f} \cdot eff_{ds,f,rr,y-1} \\ & - lock\_dem_{ds,f,rr,y-1} \end{aligned} \tag{7.7}$$

Residual locked demand equals the new locked demand of a specific period if the lifetime of the equipment ($equi\_lifet_{ds,f,rr,fy}$) installed in that period has not already been exceeded, otherwise residual locked demand is zero (assuming the sudden decay of the equipment). In constraint (7.8), *y* denotes the current year for which the equation is valid, while *fy* refers to the year when the equipment was installed. *cum_dur_per*$_y$ designates the respective cumulative duration of the periods *y* and *fy* which is required for the calculation of the difference between the two periods.

$$lock\_dem\_save_{ds,f,rr,y,fy>'2005'} = \begin{cases} \mathrm{fy} \le \mathrm{y} \wedge \mathrm{cum\_dur\_per_y} - \mathrm{cum\_dur\_per_{fy}} \le \mathrm{equi\_lifet_{ds,f,rr,fy}} : \\ \qquad lock\_dem\_new_{ds,f,rr,y,fy} \\ \mathrm{else} : 0 \end{cases} \tag{7.8}$$

For the initial equipment installed on the demand side prior to 2005 and thus the locked demand given for the *2005* period (*lock_dem*$_{ds,f,rr,y,fy='2005'}$), a slightly different pattern is applied. The remaining lifetime of this equipment is assumed to be on average half of the lifetime applied for new demand side installations. In addition, this initial equipment is assumed to decay gradually to model staggered investment decisions before the beginning of the modeling period:

$$lock\_dem\_save_{ds,f,rr,y,fy='2005'} = lock\_dem_{ds,f,rr,fy='2005'} \cdot (1 - \frac{cum\_dur\_per_{y-1}}{equi\_lifet_{ds,f,rr,fy='2005'}}) \tag{7.9}$$

III. Total cumulative production

Cumulative production *cumvol*$_{r,f,y}$, i.e. the sum of fuels units produced over time, results from cumulative production of the previous period plus production volumes of the previous period (cf. constraint 7.10). Production volumes are calculated on an annual basis and have to be multiplied with the duration of the optimization period *dur_per*$_y$ (i.e. five years).

$$cumvol_{r,f,y} = cumvol_{r,f,y-1} + \sum_{ds,rr} vol_{ds,r,f,rr,y-1} \cdot dur\_per_{y-1} \tag{7.10}$$

Cumulative production cannot exceed the maximum cumulative production, i.e. available reserves of a fuel in a specific region:

$$cumvol\_max_{r,f,y} \ge cumvol_{r,f,y} + \sum_{ds,rr} vol_{ds,r,f,rr,y} \cdot dur\_per_y \tag{7.11}$$

IV. Production capacities

In general, fuel production volumes must not exceed production capacities $cap_{r,f,y}$. However, the coefficient $cap\_max\_mult_f$ in constraint (7.12) provides the possibility for a fuel-specific production exceeding 100 percent, e.g. through overtime production or temporary technical measures increasing output volumes.

$$cap_{r,f,y} \cdot cap\_max\_mult_f \geq \sum_{ds,rr} vol_{ds,r,f,rr,y} \tag{7.12}$$

To reflect the assumed accuracy of capacity investment decisions made before the start of the model horizon, existing capacities must be utilized by at least 85 percent of their full capacity:

$$\sum_{ds,rr} vol_{ds,r,f,rr,y} \geq cap_{r,f,y} \cdot 0.85 \tag{7.13}$$

Capacities investments $cap\_inv\_units_{r,f,y}$ in one period are limited by the annual growth rate $max\_cap\_inv_{r,f}$:

$$cap\_inv\_units_{r,f,y} \leq cap_{r,f,y} \cdot (1 + max\_cap\_inv_{r,f})^{dur\_per_y} - cap_{r,f,y} \tag{7.14}$$

Also, divestments $cap\_div\_units_{r,f,y}$ must not exceed a given share of installed capacity, determined by the annual rate $max\_cap\_div_{r,f}$ which comes with a negative prefix:

$$cap\_div\_units_{r,f,y} \leq cap_{r,f,y} - cap_{r,f,y} \cdot (1 + max\_cap\_div_{r,f})^{dur\_per_y} \tag{7.15}$$

Both capacity investments as well as divestments do not take effect in the current, but in the next period to incorporate lead times into the model. Thus, the next period's production capacity is current capacity, corrected by a small coefficient cap_fail_f for unplanned capacity failures, plus additional units less divested units:

$$\begin{aligned} cap_{r,f,y+1} = {} & cap_{r,f,y} \cdot (1 + cap\_fail_{r,f})^{dur\_per_y} \\ & + cap\_inv\_units_{r,f,y} - cap\_div\_units_{r,f,y} \end{aligned} \tag{7.16}$$

V. Capacity investment and divestment costs

Costs for capacity extensions $ext\_costs_{r,f,y}$ are calculated as annuity payments based on the added capacity units multiplied by the investment cost per unit $cap\_inv\_cost_{r,f}$, cf. constraint (7.17). By modeling annuity payments, end effects at the end of the optimization period are limited.

$$\begin{aligned} ext\_costs_{r,f,y} &= cap\_inv\_units_{r,f,y} \cdot cap\_inv\_cost_{r,f} \cdot annu_f \\ &+ \sum_{fy}^{fy \le y} ext\_costs\_prev_{r,f,y,fy} \end{aligned} \tag{7.17}$$

In constraint (7.17), annuity payments from investments in earlier periods $ext\_costs\_prev_{r,f,y,fy}$ are added as long as the depreciation time $depr\_time_f$ of the capacity additions has not been exceeded. The calculation of these costs from previous periods is shown in constraint (7.18):

$$ext\_costs\_prev_{r,f,y,fy} = \begin{cases} \mathrm{fy < y \wedge cum\_dur\_per_y - cum\_dur\_per_{fy} \le depr\_time_f :} \\ \qquad cap\_inv\_units_{r,f,fy} \cdot cap\_inv\_cost_{r,f} \cdot annu_f \\ \\ \mathrm{else : 0} \end{cases} \tag{7.18}$$

Costs for capacity divestments $div\_costs_{r,f,y}$ apply immediately in the respective period. They are assumed to account for ten percent of the investment costs.

$$div\_costs_{r,f,y} = cap\_div\_units_{r,f,y} \cdot 0.1 \cdot cap\_inv\_cost_{r,f} \tag{7.19}$$

VI. Coal and gas liquefaction

To take into account the possibility of coal or gas liquefaction, the conversion into oil is modeled using the constant volume conversion ratios *coal_oil_vol_conversion* and *gas_oil_vol_conversion*. It is assumed that coal liquefaction takes place in the region of oil consumption and gas liquefaction in the region of gas production. This assumption requires slightly different constraints for the two liquefaction types. Also, for technical modeling requirements, a fifth demand sector '*CL*' had to be introduced. Its only purpose is to label coal or gas volumes needed for liquefaction.

$$vol\_rregion_{ds='CL',f='COAL',rr,y} \cdot coal\_oil\_vol\_conversion = \sum_{ds} vol\_ctl_{ds,f='OIL',rr,y} \tag{7.20}$$

$$\sum_{rr} vol_{ds='CL',r,f='GAS',rr,y} \cdot gas\_oil\_vol\_conversion = \sum_{ds,rr} vol\_gtl_{ds,r,f='OIL',rr,y} \tag{7.21}$$

Costs for liquefaction (*coal_liq_cost*$_{ds,rr,y}$ and *gas_liq_cost*$_{ds,r,y}$) result from the converted volume multiplied by the conversion cost per unit (*coal_oil_conv_cost* and *gas_oil_conv_cost*):

$$coal\_liq\_cost_{ds,rr,y} = vol\_ctl_{ds\neq'CL',f='OIL',rr,y} \cdot coal\_oil\_conv\_cost \tag{7.22}$$

$$gas\_liq\_cost_{ds,r,y} = \sum_{rr} vol\_gtl_{ds\neq'CL',r,f='OIL',rr,y} \cdot gas\_oil\_conv\_cost \tag{7.23}$$

Capacity restrictions as well as limitations and costs for capacity extensions follow the same logic as for fuel production capacities (cf. equation group IV). In constraints (7.24) to (7.28), the constraints for coal liquefaction can be found. Gas liquefaction is subject to similar constraints.

$$ctl\_cap_{rr,y} \geq \sum_{ds} vol\_ctl_{ds,f='OIL',rr,y} \tag{7.24}$$

$$ctl\_cap\_inv\_units_{rr,y} \leq ctl\_cap\_base \cdot dur\_per_{y} \tag{7.25}$$

$$ctl\_cap_{rr,y+1} = ctl\_cap_{rr,y} + ctl\_cap\_inv\_units_{rr,y} \tag{7.26}$$

$$\begin{aligned} ctl\_ext\_costs_{rr,y} = {} & ctl\_cap\_inv\_units_{rr,y} \cdot ctl\_cap\_inv\_cost_{rr,f} \\ & \cdot ctl\_annu \\ & + \sum_{fy}^{fy\leq y} ctl\_ext\_costs\_prev_{rr,y,fy} \end{aligned} \tag{7.27}$$

$$ctl\_ext\_costs\_prev_{rr,y,fy} = \begin{cases} \mathrm{fy} < \mathrm{y} \wedge \mathrm{cum\_dur\_per_{y}} - \mathrm{cum\_dur\_per_{fy}} \leq \mathrm{ctl\_depr\_time}: \\ \qquad ctl\_cap\_inv\_units_{rr,fy} \cdot ctl\_cap\_inv\_cost \cdot ctl\_annu \\ \\ \mathrm{else}: 0 \end{cases} \tag{7.28}$$

VII. Maximum fuel shares

To reflect technical restrictions on the demand side as well as convenience preferences of each demand sector (e.g. the preference of oil or gas over coal in domestic heating), some additional constraints have been introduced. Lignite may only be used in the electricity sector. In transportation, only oil and natural gas are allowed.

$$vol_{ds\neq'EL',r,f='LIGN',rr,y} = 0 \tag{7.29}$$

$$vol_{ds='TR',r,f='COAL',rr,y} = 0 \tag{7.30}$$

The usage of coal in the electricity sector as well as in the industrial and residential and commercial sectors is limited to a given share ($coal\_share_{ds,rr}$) of the final energy demand less reductions from demand elasticity.

$$\begin{aligned}&\sum_{f} vol\_rregion_{ds,f='COAL',rr,y} \cdot en\_den_{f='COAL'} \cdot eff_{ds,rr,f='COAL',y}\\&\leq fin\_dem_{ds,rr,ft='FOSSIL',y} \cdot (1-\sum_{i\_demred} demred_{i\_demred,ds,rr,y}) \cdot coal\_share_{ds,rr}\end{aligned} \tag{7.31}$$

Similarly, the share of lignite in power generation $lign\_share_{ds,rr}$ is limited to reflect the mixture of generation technologies required to adapt to the load curve.

$$\begin{aligned}&\sum_{f} vol\_rregion_{ds='EL',f='LIGN',rr,y} \cdot en\_den_{f='LIGN'} \cdot eff_{ds,rr,f='LIGN',y}\\&\leq fin\_dem_{ds='EL',rr,ft='FOSSIL',y} \cdot (1-\sum_{i\_demred} demred_{i\_demred,ds='EL',rr,y}) \cdot lign\_share_{ds='EL',rr}\end{aligned} \tag{7.32}$$

In addition, the growth of hard coal and lignite volumes is limited to incorporate the higher complexity of installing large-scale facilities on the demand side. The factor $max\_vol\_change_{ds,f,rr,y}$ denotes the maximum annual change.

$$\begin{aligned}vol\_rregion_{ds\neq'TR',f='COAL'\text{ or }'LIGN',rr,y} &\leq vol\_rregion_{ds\neq'TR',f='COAL'\text{ or }'LIGN',rr,y-1}\\&\cdot (1+max\_vol\_change_{ds,f,rr,y-1})^{dur\_per_{y-1}}\end{aligned} \tag{7.33}$$

In transportation, the share of oil may not fall below an exogenously given share $tr\_oil\_share_{tt,rr,y}$ which slightly decreases from period to period:

$$\frac{\sum_{f} vol\_rregion\_tr_{tt,f='OIL',rr,y} \cdot en\_den_{f='OIL'}}{eff\_tr_{rr,tt,y} \cdot tr\_oil\_share_{tt,rr,y}} \leq fin\_dem\_tr_{rr,tt,y} \cdot (1 - \sum_{i\_demred\_tr} demred\_tr_{i\_demred\_tr,tt,rr,y}) \tag{7.34}$$

VIII. Mapping of production volumes and capacities to production cost curve

To map the production volumes to the production cost (i.e. the cost curves in Fig. 7-4), three pointer variables have been introduced: $prod\_reg_{st,r,f,y}$, $prod\_excess_{st,r,f,y}$ and $prod\_cap_{st,r,f,y}$. Each step in the production cost curve has the step width $stepwidth_{st,r,f,y}$ assigned, indicating the volume available for production at a certain cost level. *prod_reg*, *prod_excess* and *prod_cap* track how much of the volume per cost step has already been used.

prod_reg indicates the regular costs for production whereas *prod_excess* is used to calculate a cost markup depending on the degree of capacity utilization. *prod_cap* monitors the production capacity. This split is required to allow the separate calculation of fixed and variable production costs.

In each region and for each fuel, the sum of *prod_reg* over all steps must be at least equal to the produced fuel volume (cf. constraint 7.35). At the same time, *prod_reg* related to one step must not exceed the corresponding step width, as shown in constraint (7.36).

$$\sum_{st} prod\_reg_{st,r,f,y} \geq \sum_{ds,rr} vol_{ds,r,f,rr,y} \cdot dur\_per_{y} \tag{7.35}$$

$$\sum_{fy}^{fy \leq y} prod\_reg_{st,r,f,fy} \leq stepwidth_{st,r,f,y} \tag{7.36}$$

Also, only a given fraction (defined by pa_limit_f) of each step can be produced per year. This constraint emulates the fact that not all capacities produce from the cheapest reserves but are spread over an array of reserves with differing production costs:

$$prod\_reg_{st,r,f,y} \leq \frac{stepwidth_{st,r,f,y}}{pa\_limit_{f}} \cdot dur\_per_{y} \tag{7.37}$$

Similar restrictions apply for *prod_excess*, in addition it may not exceed *prod_reg*. It is important to note that *prod_excess* does not indicate production volumes in addition to the volumes linked to *prod_reg*. Instead, *prod_excess* is only a marker required to calculate the share of the total production exceeding certain levels of capacity utilization (cf. Fig. 7-7).

$$\sum_{fy}^{fy \leq y} prod\_excess_{st,r,f,fy} \leq stepwidth_{st,r,f,y} \tag{7.38}$$

$$prod\_excess_{st,r,f,y} \leq \frac{stepwidth_{st,r,f,y}}{pa\_limit_f} \cdot dur\_per_y \tag{7.39}$$

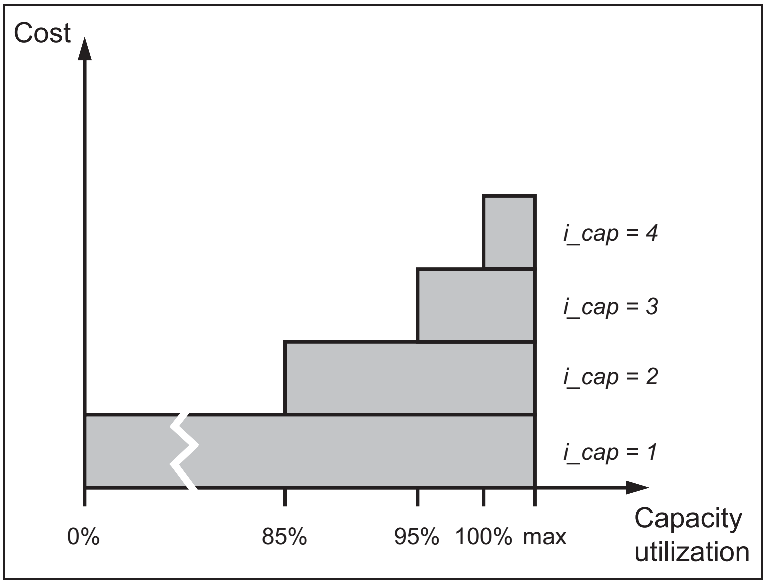
$$prod\_excess_{st,r,f,y} \leq prod\_reg_{st,r,f,y} \tag{7.40}$$

prod_excess is mapped to another variable, $cap\_margin_{i\_cap,r,f,y}$, that indicates the degree of capacity utilization (cf. constraints 7.41 and 7.42).

$$\sum_{st} prod\_excess_{st,r,f,y} \geq cap\_margin_{i\_cap,r,f,y} \cdot dur\_per_y \tag{7.41}$$

$$cap\_margin_{i\_cap,r,f,y} \geq \sum_{ds,rr} vol_{ds,r,f,rr} - cap_{r,f,y} \cdot cap\_lim_{i\_cap,r,f} \tag{7.42}$$

These equations are required to calculate production costs as a function of capacity utilization while keeping the model linear at the same time. To achieve this, a stepwise markup is introduced with *i_cap* as the index for the capacity utilization step $cap\_lim_{i\_cap,r,f}$. In the end, a cost structure as sketched in Fig. 7-7 is achieved.



Source: Own representation

Fig. 7-7: Schematic curve of production cost markup

prod_cap is used to calculate fixed costs related to installed production capacity. Similar to *prod_excess*, *prod_cap* does not represent additional production volumes but only links production to capacities. Again, its calculation is analogous to the above approaches:

$$\sum_{st} prod\_cap_{st,r,f,y} \geq cap_{r,f,y} \cdot dur\_per_y \tag{7.43}$$

$$\sum_{fy}^{fy \leq y} prod\_cap_{st,r,f,y} \leq stepwidth_{st,r,f,y} \tag{7.44}$$

$$prod\_cap_{st,r,f,y} \leq \frac{stepwidth_{st,r,f,y}}{pa\_limit_f} \cdot dur\_per_y \tag{7.45}$$

IX. Fixed and variable production costs

The variables *prod_reg*, *prod_excess* and *prod_cap* have been linked to the production volumes in the above equations and are now applied to the production cost curves. The parameter $coststep_{st,f}$ specifies the total production costs of a unit at a given step of a cost curve. Fixed costs $fix\_prod\_cost_{r,f,y}$ occur regardless whether production capacities are used for production or not. They cover e.g. for exploration costs, capital costs and other fixed costs. Since the production cost curve contains data only on a full cost basis, a share $share\_fixed\_costs_f$ for the costs is applied:

$$fix\_prod\_cost_{r,f,y} = \sum_{st} prod\_cap_{st,r,f,y} \cdot coststep_{st,f} \cdot share\_fixed\_costs_f \tag{7.46}$$

Variable costs $var\_prod\_cost_{r,f,y}$ consist of costs related to normal production plus a markup $excess\_prod\_mult_{i\_cap,r,f}$ depending on the degree of capacity utilization (cf. Fig. 7-7).

$$\begin{aligned} var\_prod\_cost_{r,f,y} = {} & \sum_{st} prod\_reg_{st,r,f,y} \cdot coststep_{st,f} \cdot (1 - share\_fixed\_costs_f) \\ & + \sum_{i\_cap,st} (prod\_excess_{i\_cap,st,r,f,y} \cdot coststep_{st,f} \\ & \cdot excess\_prod\_mult_{i\_cap,r,f}) \end{aligned} \tag{7.47}$$

Another cost element that needs to be considered is the royalty paid to the resource owners as a result of scarcity. This has been implemented in a way that volumes remaining in situ at the end of the optimization period are valued with a fuel-specific terminal or residual value[91].

The total value of the remaining fuel volumes $scar\_cost_{r,f,y}$ is deducted from the sum of the other costs in the objective function, which explains the negative prefix for this cost type.

$$\begin{aligned} scar\_cost_{r,f,y} = {} & -(cumvol\_max_{r,f,y} - (cumvol_{r,f,y} + \sum_{ds,rr} (vol_{ds,r,f,rr,y} \cdot dur\_per_y))) \\ & \cdot \frac{res\_val_{r,f}}{(1+ir)^{cum\_dur\_per_{y='2050'} - cum\_dur\_per_y}} \end{aligned} \tag{7.48}$$

Note that constraint (7.48) is formulated in a way so that it can be applied to calculate the residual value in any year. However, in the objective function only the result in *y='2050'* is accounted for.

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[91] Based on expert interviews, the following residual values have been assumed: 15 \$/t for hard coal, 750 \$/t = 102 \$/bbl for oil, 2.5 \$/t for lignite and 80 \$/1000m³ for natural gas.

X. Transportation costs

Transportation costs in the model consist of two parts: Costs for intra-regional transportation $tr\_intrareg\_cost_{tt,r,f,rr,y}$, i.e. within the same region (cf. constraint 7.49), and costs for trans-regional transportation $tr\_transreg\_cost_{tt,r,f,rr,y}$, i.e. between different regions (cf. constraint 7.50). Intra-regional transportation costs (e. g. rail or inland water transport) occur for every fuel unit produced (variable $tr\_vol\_intrareg_{tr\_type,r,f,rr,y}$), from the production site to the regional transshipment center. As the volumes shipped within one region and between regions are not necessarily identical, two separate constraints are required.

$$tr\_intrareg\_cost_{tr\_type,r,f,rr,y} = \begin{cases} \mathrm{r} = \mathrm{rr} : (port\_dist_{tr\_type,r,f,rr} \cdot tr\_cost\_slope_{tr\_type,f} + tr\_cost\_interc_{tr\_type,f}) \\ \qquad \cdot tr\_vol\_intrareg_{tr\_type,r,f,rr,y} \cdot dur\_per_{y} \\ \\ \mathrm{else}: 0 \end{cases} \tag{7.49}$$

Trans-regional transportation costs only accrue for fuel units shipped from one region to another, indicated by the variable $tr\_vol\_transreg_{tr\_type,r,f,rr,y}$.

$$tr\_transreg\_cost_{tr\_type,r,f,rr,y} = \begin{cases} \mathrm{r} \neq \mathrm{rr} : (port\_dist_{tr\_type,r,f,rr} \cdot tr\_cost\_slope_{tr\_type,f} + tr\_cost\_interc_{tr\_type,f}) \\ \qquad \cdot tr\_vol\_transreg_{tr\_type,r,f,rr,y} \cdot dur\_per_{y} \\ \\ \mathrm{else}: 0 \end{cases} \tag{7.50}$$

A linear relation between transportation distance $port\_dist_{tt,r,f,rr}$ and cost is assumed. This is implemented by multiplying distance with the constant cost factor $tr\_cost\_slope_{tt,f}$. A constant summand $tr\_cost\_interc_{tt,f}$ is added to reflect non-distance related handling costs (e.g. reloading).

Two further equations ensure that the volume flows within and between regions add up correctly:

$$\sum_{tr\_type,rr} tr\_vol\_intrareg_{tr\_type,r,f,rr,y} = \sum_{ds,rr} vol_{ds,r,f,rr,y} + \sum_{ds,rr} vol\_gtl_{ds,r,f,rr,y} \tag{7.51}$$

$$\sum_{tr\_type} tr\_vol\_transreg_{tr\_type,r,f,rr,y} = \begin{cases} \mathrm{r} \neq \mathrm{rr} : \sum_{ds} vol_{ds,r,f,rr,y} \\ \mathrm{else}: 0 \end{cases} \tag{7.52}$$

XI. CO_2 emission costs

Costs for CO_2 emissions $co2\_cost_{ds,f,rr,y}$ result from the emission volume in tons (calculated by multiplication of fuel volume, energy density and the fuel-specific CO_2 emission $spec\_co2\_em_f$) multiplied by the emission costs $co2\_price_{ds,rr,y}$ in US-$/t CO_2 (cf. constraint 7.53). CO_2 emissions are caused by combustion of fossil fuels as well as by coal liquefaction. *ctl_spec_co2_em* specifies the volume of CO_2 emitted per volume unit of coal converted to oil.

$$\begin{aligned} co2\_cost_{ds,f,rr,y} = {} & (vol\_rregion_{ds,r,f,rr,y} \cdot en\_den_f \cdot spec\_co2\_em_f \\ & + vol\_ctl_{ds,f,rr,y} \cdot ctl\_spec\_co2\_em) \\ & \cdot co2\_price_{ds,rr,y} \cdot dur\_per_y \end{aligned} \tag{7.53}$$

XII. Objective function

In the objective function (7.54), all costs are discounted to 2005 (using the discount factor npv_fact_y) and added up. The optimization run in GAMS finds the solution with the lowest total cost over the entire period.

$$\begin{aligned} & \sum_y \Big\{ \big(\sum_{r,f} var\_prod\_cost_{r,f,y} + \sum_{r,f} fix\_prod\_cost_{r,f,y} \\ & + \sum_{ds,rr} coal\_liq\_cost_{ds,rr,y} + \sum_{ds,r} gas\_liq\_cost_{ds,r,y} \\ & + \sum_{tt,r,f,rr} tr\_intrareg\_cost_{tt,r,f,rr,y} + \sum_{tt,r,f,rr} tr\_transreg\_cost_{tt,r,f,rr,y} \\ & + \sum_{ds,f,rr} co2\_cost_{ds,f,rr,y} + \sum_{r,f} div\_cost_{r,f,y} \\ & + \sum_{r,f} ext\_cost_{r,f,y} + \sum_{rr} ctl\_ext\_costs_{rr,y} + \sum_{r} gtl\_ext\_costs_{r,y} \big) \cdot npv\_fact_y \Big\} \rightarrow \mathbf{min} \end{aligned} \tag{7.54}$$

After the optimization, prices of fossil fuels are calculated as shadow prices of constraint (7.1)[92].

7.1.6 Stochastic enhancement

So far, perfect foresight and the absence of any uncertainties have been assumed for the deterministic optimization. Now, stochastic shocks are applied to emulate real world conditions (cf. the discussion of decisions under uncertainty in

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[92] Cf. section 6.4 for a discussion of the economic meaning of shadow prices.

chapter 3), e.g. when the final energy demand deviates from expectations or when fuel reserve volumes are reassessed and adjusted.

As the discussion in chapter 5 has made clear, there are many potential factors that influence the long-term price formation process of fossil primary fuels. However, to keep model complexity and computation time at a manageable level, a selection has to be made as to which parameters are included stochastically. In the current model version, four key drivers are chosen to be modeled stochastically: available crude oil reserves and resources, available natural gas reserves and resources, final energy demand and CO_2 emission costs. Based on the review in chapter 5, it can be assumed that these four sources of uncertainty are the most relevant ones that will impact the balance of energy supply and demand during the period of consideration, at least when considering only fundamental key drivers.

For each of these four parameters, three cases are defined, called the *LOW*, *MID* and *HIGH* cases[93]. They reflect the possible status of each parameter for every calculation point between the years *2010* and *2050*, leading to $3^4 = 81$ possible scenarios per period. This approach is based on the three-point discrete-distribution by Keefer (1994), cf. subsection 6.4.4. The year *2005* is an exception to the rule: Since here fuel prices are ex post known, only one scenario with all stochastic parameters set to the *MID* case is calculated for *2005*, adjusted to result in the actual observed prices.

The equation framework of the stochastic model is identical to the deterministic version. Only in a few equations, corrective factors are included. They provide greater flexibility for adaptations in the start year of the current optimization run, alleviating the impact of the stochastic shocks. The two most important examples are the reduction of the locked demand, if the total demand has been reduced compared to the previous model period, and a temporary ease of the maximum share of a fossil fuel in a demand sector (cf. equations discussed in subsection VII above).

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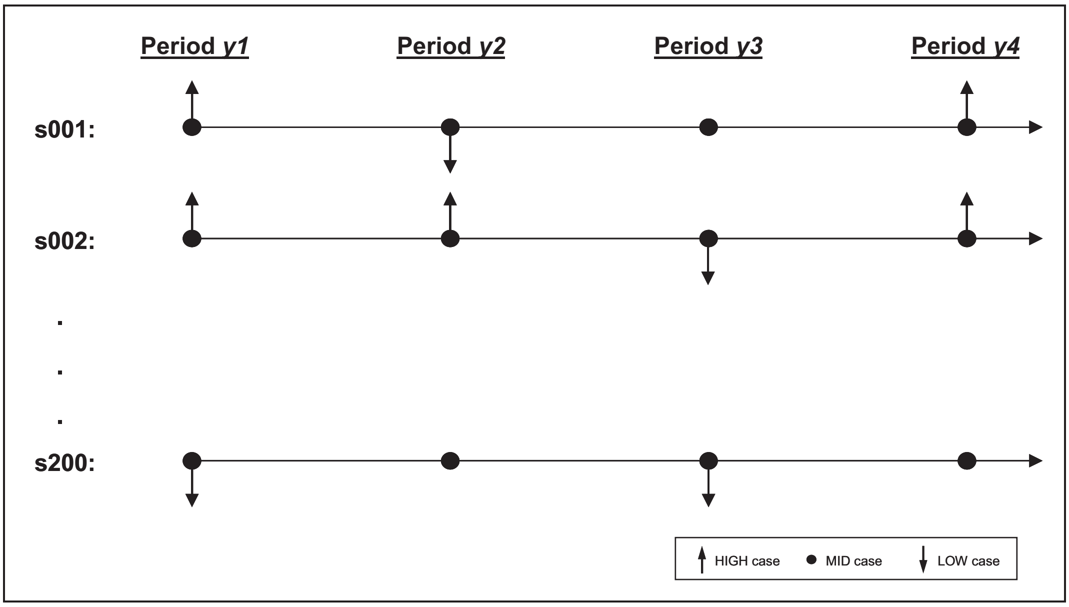
[93] In a way, the formulation of these three cases can be considered as very simple version of the scenario planning approach described in subsection 3.2.2.2. Following the approach by Coates (2000) described there, chapter 4 and 5 define both the universe of concern relevant for this thesis (step 1 of the Coates approach), as well as identified the key uncertain parameters that will shape the future development (step 2). After that, the definition of the cases applied in this thesis is of course not as sophisticated as the scenarios in the Coates approach. However, this is not required, as the model merges the influence from the different factors into a one-dimensional, easy-to-understand model result.

Prior to the optimization run, the values of the four stochastic inputs for each period are determined using a Monte-Carlo simulation. *HIGH* and *LOW* cases are set to occur with a probability of 30 percent each, *MID* cases with a probability of 40 percent[94]. In total, 200 scenarios[95] are created. Fig. 7-8 shows a schematic representation of the Monte-Carlo simulation for the determination of stochastic input values (only one instead of four input values displayed for the sake of simplicity).



Source: Own representation

Fig. 7-8: Schematic representation of Monte-Carlo simulation results

According to the above procedure, the first optimization includes the entire planning horizon. The stochastic parameters in each period are set based on the respective cases in the first period *y1*. After an optimal solution has been found, the results for the first period are saved and the respective variables fixed in the model. In the second model run, all stochastic parameters in *y2* and later are set according to the cases from the Monte Carlo simulation for the period *y2*. The first period is not considered any longer since these decisions already have been made.

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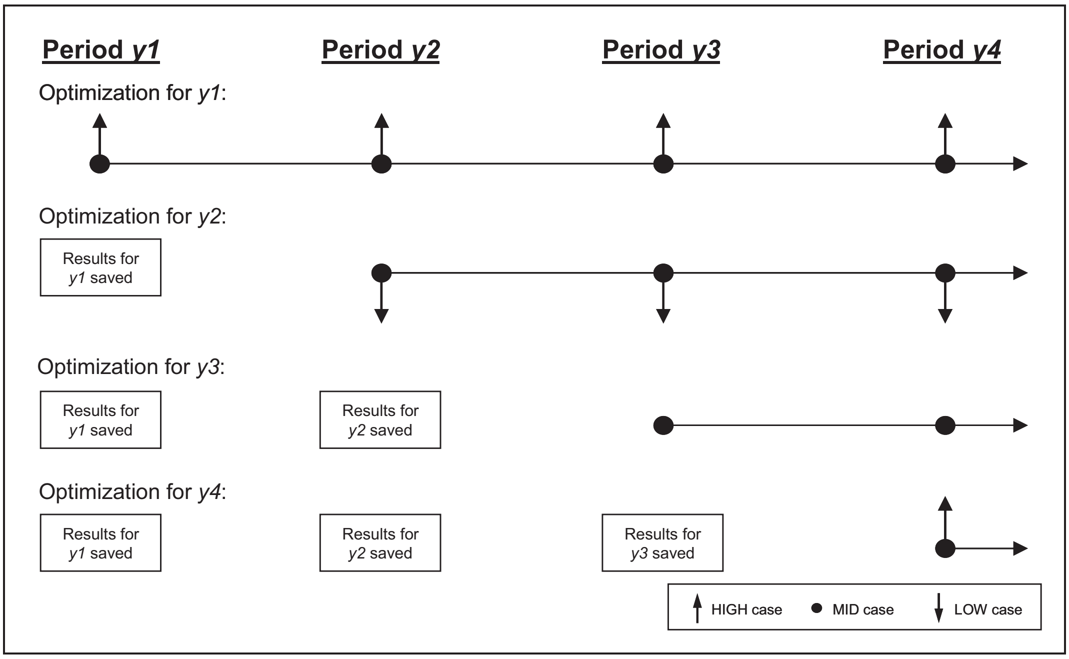
[94] Based on own assessment.

[95] A scenario is defined as a complete set of cases for all four stochastic parameters from 2005 to 2050.

A schematic representation of the stochastic model can be found in Fig. 7-9 (based on the illustrative results of the Monte Carlo simulation for scenario *s001* in Fig. 7-8). Each horizontal line symbolizes one execution of the deterministic model. A stochastic optimization ends after the model run for the last period has been finalized. In the top line for the model run starting in period *y1*, all cases are set to HIGH, as given by the Monte Carlo simulation (cf. node for *y1* in scenario *s001* in Fig. 7-8). In the second line for the optimization starting in period *y2*, the results for *y1* are already given from the first optimization. All cases are now set according to the Monte Carlo results for the period *y2* in scenario *s001* (cf. second node in top line in Fig. 7-8). This process is carried out for all 10 nodes in all 200 scenarios, resulting in 2,000 single optimization runs in the stochastic part of the model.



Source: Own representation

Fig. 7-9: Schematic representation of stochastic model run for scenario *s001*

To facilitate the program loops over different scenarios and start periods, some additional program routines are required (cf. program structogram[96] in Fig. 7-10). It illustrates the model flow as already shown in Fig. 7-8 and Fig. 7-9.

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[96] Also called Nassi-Shneiderman diagram after Isaac Nassi and Ben Shneiderman, cf. Nassi and Shneiderman (1973).

```
Loop over all scenarios (s001 - s200)
    Initialize variables
    Loop over start period (y2005 - y2050)
        Assign cumvol_max according to scenario
        If cumvol(r,f) > cumvol_max(r,f)
            cumvol_max(r,f) = cumvol(r,f)
        Assign $CO_2$ emission costs and final energy demand acc. to scenario
        Calculate correction factors, e.g. for locked demand
        Adjust prod-variables to stepwidth changes, if required
        SOLVE optimization problem
        Save variable results of start period required for next model run
        Calculate shadow prices of start period
```

Source: Own representation

Fig. 7-10: Structogram for stochastic enhancement

The first line of Fig. 7-10 stipulates the loop over all 200 scenarios, i.e. all instructions following this command are carried out 200 times. First of all, the variables used for each scenario are initialized. This means setting them to their initial values (e.g. production capacities) and removing boundaries and saved values (e.g. cumulative production or capacities in later model periods) from previous calculations. Then a second loop is started: It runs over all periods of the current scenario. This corresponds to the process illustration in Fig. 7-9. In the first step within the period loop ("Assign *cumvol_max* according to scenario"), the stochastic cases of crude oil and natural gas availability for the current period in the current scenario are looked up in the Monte Carlo results. Based on these values, the maximum cumulative production values (cf. constraint 7.11) and the production cost curves (defined by the parameter $stepwidth_{st,r,f,y}$, cf. the explanation for the equation group VIII above) are assigned for oil and natural gas in each region.

When available fuel volumes are revised downwards from one period to the next based on the Monte Carlo results, e.g. when oil availability is changed to *LOW* from a *MID* or even *HIGH* case, it may occur that the cumulative production from earlier periods is already higher than the new maximum cumulative production volume. Because such a change would violate constraint (7.11), the maximum cumulative production volume needs to be revised to the current cumulative production volume from earlier model periods. In the structogram, this process can be found in the second box in the loop over all periods.

The third box refers to the assignments of CO_2 emission costs and final energy demand, which follow the same approach as the assignment of fuel volumes described above. For these two stochastic parameters, no process for data adjustment needs to be implemented because the values here can be chosen without interference with earlier calculations.

The calculation of correction factors as shown in the fourth line is required only if the assignment of final energy demand for the current period results in a demand figure lower than the locked demand (cf. subsection 7.1.3 and equation group II). This can be the case e.g. if final energy demand in the previous period had been set to the *HIGH* case, leading to a high locked demand. If now the case for the final energy demand in the current period is *LOW*, it may occur that total final energy demand is lower than the locked demand. This hardly makes sense and also leads to solution errors in the equations. For this purpose, temporary correction factors need to be calculated that proportionally reduce the locked demand.

The adjustment of *prod*-variables (cf. constraint group VIII) in the fifth line is closely related and very similar to the adjustment of the maximum cumulative production volumes described above. As each step width in each production cost curve is reduced downwards if the cases of fuel availability worsen from one period to the next, constraints (7.36), (7.38) and (7.44) might be violated. These equations postulate that the *prod*-variables may not exceed $stepwidth_{st,r,f,y}$. Thus, the *prod*-variables need to be adjusted, too, if required.

The sixth box "*SOLVE optimization problem*" indicates the point where the optimization problem is actually solved based on the previous inputs and data adjustments. The objective functions and constraints are identical to those described for the deterministic part in subsection 7.1.5.

After the solution of the optimization problem, the variables required for the next period (e.g. cumulative production as well as available production and liquefaction capacities) are saved (as indicated by the boxes on the left hand side in Fig. 7-9). Finally, the shadow prices of constraint (7.1) are calculated and used as results for the fuel prices.

7.2 Model input

Nature and quality of the results of any model are determined by both model structure, i.e. primarily the equations described above, and model input data. In the following, the key data assumptions are introduced here.

All input data is checked for plausibility and consistency, however an in-depth analysis of all data points obviously is impossible due to lack of time and proficiency. Auffhammer (2007) also points to another point to be considered when using external data sources. He describes the concept of an asymmetric loss function indicating the preference of modelers for an over- or under-prediction of results. He postulates that it is mandatory "*to understand how costly the producer of the forecasts finds over predictions relative to under predictions of the variable of interest*" (Auffhammer 2007, p. 103). It can be shown that in long-run EIA forecasts, GDP is systematically over-predicted and energy intensity is systematically under-predicted. Auffhammer concludes that while users of forecast data usually assume that forecasters do not have any preferences, this is often not the case. However, to interpret and use forecast data correctly and optimally, the preferences of the forecasters need to be known.

It is not possible to test the data used as input for this model for a symmetric or asymmetric loss function. Instead, a symmetric loss function, i.e. indifference regarding over vs. under prediction for all input data has to be assumed.

In the following, the underlying sources and assumptions for the key data of the model are presented. It needs to be emphasized that the data set at hand is based on the findings and assumptions of the modeler following the conclusions from the review of schools of thought and price key drivers in the chapters 4 and 5. The split of the model into structure and input data (cf. Fig. 7-2) easily permits the application of data based on differing sets of assumptions, depending on the user preferences. Due to the flexibility of the model, such a replacement of input data sets can be carried out while the structure of the model remains unchanged.

7.2.1 Fuel availability

As discussed several times before, assumptions about fuel availability are probably most crucial for the model results. Tab. 7-3 shows the global sum of available fuel volumes per fuel and per stochastic case[97]. This table is meant to provide an overview on the dimensions only. In the model data, each of the above numbers

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[97] For hard coal and lignite, only the MID case is shown because the fuel availability of these fuels is not implemented stochastically at the moment.

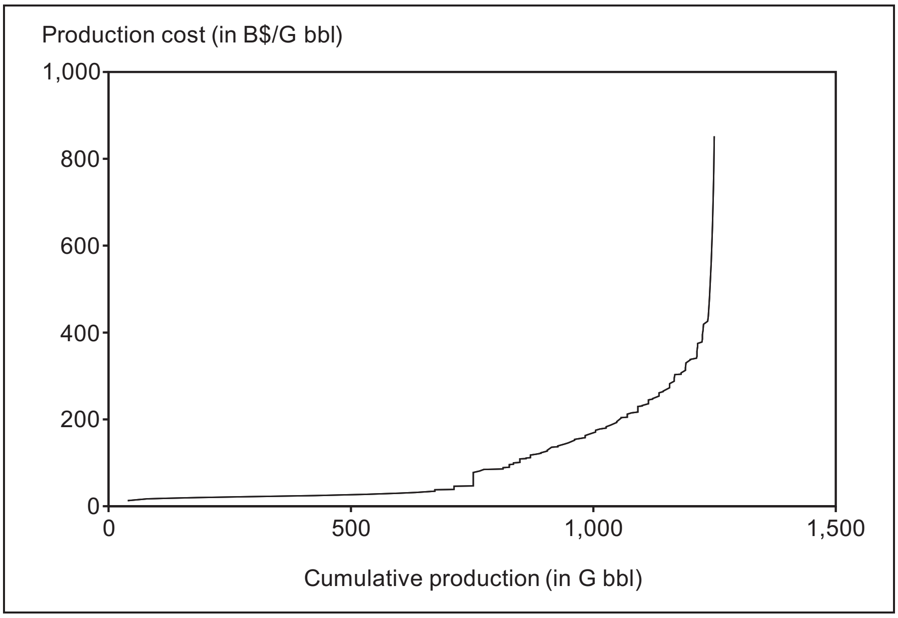
is broken down into the seven global regions. Data is taken from BGR (2003), (2004), the link to production costs (also cf. the next subsection 7.2.2) is based on the methodology developed by Markandya, Mason et al. (2000). It must be noted that especially for natural gas, the change in fuel availability is tremendous from case to case. Following Odell (2004), this is due to the fact that for non-conventional gas reserves and resources, only speculative data exists so far as large conventional reserves are so significant that non-conventional deposits have hardly been of interest until today.

	LOW case	**MID case**	**HIGH case**
Hard coal (in Gt)	n/a	4,741.8	n/a
Crude oil (in G bbl)	2,747.4	3,759.7	4,440.9
Lignite (in Gt)	n/a	1,128.6	n/a
Natural gas (in Gm³)	537,687.0	2,841,304.0	17,225,387.6

Source: Based on Markandya, Mason et al. (2000), BGR (2003), (2004), and own assessments

Tab. 7-3: Global fuel availability per fuel and stochastic case

A crucial element in the model is the tight connection between volume and production costs. This is illustrated by the production cost curves as explained in subsection 7.1.2. For a better understanding, the above example (cf. Fig. 7-4) of a production cost curve is shown again in Fig. 7-11.



Source: Own representation based on Markandya, Mason et al. (2000), updated with data from BGR (2003), (2004)

Fig. 7-11: Production cost curve (Crude oil, Middle East, MID case)

In Fig. 7-11, the maximum production volume of crude oil in the Middle East for the MID case is about 1,250 G bbl – indicated by the right-most value of the curve on the axis of abscissae. While this is the volume for one region only, the figures in Tab. 7-3 show the sum of all regions, which is for the example of crude oil in the MID case 3,759.7 G bbl. What can also be seen in Fig. 7-11, is that the fuel volume is mapped in small steps to the respective production costs on the axis of ordinates.

The fuel volumes from Tab. 7-3 contain both conventional and non-conventional[98] fuel reserves as well as best estimate (cf. definitions in section 4.1) resource figures. For this reason, fuel volumes may seem very high at first sight. However, it should be noted that the upper share of each volume figure is connected to high production costs. Looking at Fig. 7-11 again, a sudden change in cost can be observed at about 750 G bbl. This is where the transition from cheaper conventional fuel reserves to more expensive non-conventional reserves and also resource volumes occurs.

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[98] Tar sands, heavy oil and shale oil for crude oil reserves and coalbed methane, tight gas, gas hydrates and acquifier gas for natural gas reserves. Cf. e.g. BGR (2003), (2004) for further details and explanations on non-conventional fossil fuels.

7.2.2 Production costs and markups

The production cost data employed builds on the methodology developed by Markandya, Mason et al. (2000) in the SAUNER project. Their production cost curves for crude oil and natural gas (cf. Mason 2000a, 2000b) are updated with data from BGR (2003), (2004). For hard coal and lignite, production cost curves are developed based on the same methodology.

The range of production costs can be taken from Tab. 7-4. It should be noted that the cost maximum is a theoretical value that is never reached in the optimization runs. Again, this is due to the large range of available fuel volumes included in the data set, as explained in the above subsection 7.2.1 on fuel availability.

Fuel	Min. production cost	Max. production cost	Cost multiple (on top)
Hard coal	12.3 US-$/t	128 US-$/t	0.1x – 1.8x
Crude oil	1.8 US-$/bbl	116 US-$/bbl	0.3x – 7.0x
Lignite	5.6 US-$/t	42 US-$/t	0.0x – 1.2x
Natural gas	18 US-$/1000 m³	932 US-$/1000 m³	0.3x – 1.5x

Source: Based on Markandya, Mason et al. (2000),
BGR (2003), (2004), BP (2005), (2006),
OPEC (2007) and own assessments

Tab. 7-4: Production costs and markups

Tab. 7-4 also provides information on the range of cost markups that have to be included to come to meaningful results, i.e. results for 2005 calculated prices that come close to observed market prices. The markups are calculated based on data on spare production capacities and oil prices taken from BP (2005), (2006) and OPEC (2007). Costs multiplied with these markups are added on top of the production costs (cf. parameter $excess\_prod\_mult_{i\_cap,r,f}$ in equation 7.47 and Fig. 7-7). They reflect e.g. the effect of exercised market power, cartel rent and other key drivers not included in the underlying fundamental cost data. Generally speaking, the maximum value of the range for each fuel in Tab. 7-4 has been used for $i\_cap = 1$, i.e. has been applied to the entire production volume. Most noticeable is the high value of *7* for crude oil. This is due to the fact that the current high oil prices cannot be explained by costs based on fundamental data only.

7.2.3 Final energy demand

For the purpose of this thesis, only the share of final energy demand projected to be covered by fossil fuels is considered. As far as possible, demand data is taken from IEA (2004). The report distinguishes between final energy demand covered by fossil, nuclear, renewable and other fuels.

For the demand sectors *Electric Power*, *Industrial* and *Residential & Commercial*, the *MID* case data for the demand for final energy demand, is based on the IEA Reference Scenario. Demand data beyond 2030 is extrapolated based on adjusted 2005 - 2030 growth rates. Data for the *LOW* case is taken from the Alternative Policy Scenario of the same report. The *HIGH* case data is based on an application of the adjusted percental difference between Alternative Policy and Reference IEA scenario.

Final energy demand is calculated in TWh_{el} for the *Electric Power* sector and in TWh_{th} for the *Industrial* and *Residential & Commercial* sectors. Data for *Industrial* and *Residential & Commercial* only includes final energy demand that is not covered by electricity.

The fourth demand sector, *Transportation*, falls into two subsectors, *Passengers* and *Freight*. Demand is measured in *Gpkm* and *Gtkm*. Data for the *MID* case is based on the Reference Scenario from WBCSD (2004). *LOW* and *HIGH* cases are calculated by applying the same percentages as used for the three other demand sectors.

For equipment lifetimes on the demand side, the following assumptions are made:

Sector	Fuel	Lifetime in years
Electricity	Hard coal	40
	Oil	30
	Lignite	40
	Natural Gas	30
Industry	Hard coal	30
	Oil	30
	Lignite	n/a
	Natural Gas	30
Residential & Commercial	Hard coal	20
	Oil	20
	Lignite	n/a
	Natural Gas	20
Transportation - Passengers	Hard coal	n/a
	Oil	12
	Lignite	n/a
	Natural Gas	12
Transportation - Freight	Hard coal	n/a
	Oil	17
	Lignite	n/a
	Natural Gas	17

Source: Based on BMF (2003), Pfaffenberger and Hille (2004), Weber (2005b) and own assessments

Tab. 7-5: Equipment lifetimes

7.2.4 CO_2 emission costs

Although CO_2 emission costs are not included in the calculation of the unit prices for fossil fuels, they play an important role when deciding between fossil fuels with different specific CO_2 emissions. Unfortunately, the development of CO_2 emission costs after the expiration of the Kyoto Protocol in 2013 is highly ambiguous and probably constitutes the most important uncertainty in the context of future usage of fossil fuels.

The costs for an emission of one ton CO_2 are derived from discussions with corporate planners in the utility industry and range from 0 \$/t CO_2 to more than 150 \$/t in 2050 (in US-$\$_{2005}$). In its current status, the model uses exogenously given prices. The endogenous determination of CO_2 emission costs might be carried out in future stages of development of the model.

7.2.5 Energy efficiency and technology advancement

Technical improvement of existing technologies is reflected in the model by an increase of the energy conversion efficiency. For the demand sectors *Electric Power*, *Industrial* and *Residential & Commercial*, data on energy efficiency rates originate from EU (2003b), IEA (2004), EIA/DOE (2005) and from own calculations. For the *Transportation* sector, efficiency rates have been taken from the Reference Scenario of WBCSD (2004).

Developments of other new technologies relevant for the energy conversion of fossil fuels are not explicitly modeled. One possible technology for future implementation can be the so-called *CO_2-free* power plants in the *Electricity* sector, i.e. the sequestration of CO_2.

7.2.6 Production and liquefaction capacities

The initial endowment with fuel production capacities is based on the 2004 production volume data from BGR (2003), (2004). Maximum annual capacity growth rates have been calculated based on data from BP (2005), (2006). Tab. 7-6 provides an overview on the range of allowed annual percental capacity extensions per fuel.

Fuel	Max. annual capacity growth rate
Hard coal	3.0% – 10.0%
Crude oil	2.0% – 2.5%
Lignite	4.0% – 7.5%
Natural gas	4.5% – 8.5%

Source: Based on BP (2005), (2006)
and own assessments

Tab. 7-6: Maximum annual capacity extension

Costs for capacity extensions for crude oil and natural gas production are taken from Masseron (1990) and updated to reflect 2005 prices. Investment costs for hard coal and lignite are based on assessments from Administration of Rostov region (2006), National Development Corporation (1998), Mimuroto (2002), Government of India (2002 - 2003) and WDR (2005). The range of investment costs is depicted in Tab. 7-7.

Fuel	Investment costs	Unit
Hard coal	$7.4 \cdot 10^9 - 3.3 \cdot 10^{11}$	US-$\$_{2005}$/Gt/a
Crude oil	$7.5 \cdot 10^9 - 2.9 \cdot 10^{10}$	US-$\$_{2005}$/G bbl/a
Lignite	$7.4 \cdot 10^9 - 1.9 \cdot 10^{10}$	US-$\$_{2005}$/Gt/a
Natural gas	$5.8 \cdot 10^{10} - 2.4 \cdot 10^8$	US-$\$_{2005}$/Gm³/a

Source: Based on Administration of Rostov region (2006),
National Development Corporation (1998), Mimuroto (2002),
Government of India (2002 - 2003), WDR (2005)
and own assessments

Tab. 7-7: Capacity investment costs

For coal and gas liquefaction, capacity and cost information are collected from press clippings due to the lack of comprehensive reliable data. Key sources have been Chemlink Australia (1997), Gray (2005) and Bloomberg (2006). Tab. 7-8 provides an overview on liquefaction capacities in 2005 and 2010.

	2005 capacities	2010 capacities	Max. annual extension
CTL	44 mill. bbl/a	≥ 2005 capacity	150 mill. bbl/a
GTL	0	253 mill. bbl/a	150 mill. bbl/a

Source: Based on Chemlink Australia (1997),
Gray (2005) and Bloomberg (2006)
and own assessments

Tab. 7-8: Liquefaction capacities

Investment costs for liquefaction capacities are assumed to account for $1.7 \cdot 10^8$ US-$\$_{2005}$/mill. bbl/a for coal and $8.3 \cdot 10^7$ US-$\$_{2005}$/mill. bbl/a for gas liquefaction, based on the same sources as for the capacity data.

7.2.7 Transportation costs

The fuel costs calculated in the model include transportation from the production site to a representative transshipment center in the region of consumption. This can be either in a different or the same region where the fuel is produced.

In case the regions where a fuel unit is produced and where it is consumed are not identical, the transportation costs consist of the costs from the production site to the transshipment center of the exporting region, plus costs for transportation from one region to another. This means that fuel prices calculated are free border and distribution costs within the destination region are not included.

For each region, representative sites for production and transshipment centers are identified. Distances between sites both within the same region and between regions are evaluated, primarily based on Google Maps (2005) and Distances.com (2005). Available means of transportation are ship, pipeline and ground transport (i.e. truck, train or barge). A matrix of possible routes of transportation defines which combinations of origin, destination, fossil fuel and means of transportation are technically and geographically feasible and thus allowed in the model.

Cost data originates from Gerling and Rempel (2003) and is updated to reflect costs in US-$\$_{2005}$. A constant cost summand is added to incorporate non-distance-related handling costs (e.g. reloading).

Currently, transportation capacities are unlimited in the model. Also, costs are not related to crude oil prices. The former point is due to the large data research required to assess current transport capacities and their development. Given the long time periods of the model, the distortion of results due to this generalization is likely to be negligible. The latter deficiency might play a more important role. However, an adaptation of transportation costs to fuel costs has been left out intentionally to avoid non-linear equations that increase computation time significantly.

7.2.8 Interest rate, exchange rate and currency

The interest rate *ir* used for discounting purposes in the model is set to 7 percent. It is thus higher than a so-called *social discount rate* often used e.g. in models calculating the costs of global warming (cf. e.g.Voss 2007) and is based on the cost of capital employed[99].

The importance of exchange rates has already been highlighted in subsection 5.3.3. Since an accurate forecast of exchange rates over a very long period as required for the purpose of this thesis is hardly possible, it must be assumed that European utilities are hedged against exchange rate fluctuations, an assumption

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[99] Also cf. Weber (2005b), pp. 262 - 265, for an assessment of the appropriate discount rate.

probably not that far from reality given the size and range of operations of large electricity producers. The exchange rate in this model has been set to 1.25 US-$/€. However, all results for fossil fuels are shown in US-$$_{2005}$ in real terms.

7.3 Results for Western Europe

In this section, the results of the optimization model[100] are presented. As explained above, shadow prices of constraint (7.1) are interpreted as fuel price results[101]. Only the fuel price results for Western Europe are presented and discussed. However, the model is able to deliver corresponding results, i.e. prices with the same level of detail and precision, for all six other global regions as well. The limitation to Western Europe is due to the proposed application of the results in a model of the German electricity industry (cf. chapter 8).

All prices are import prices free border at the ARA harbors. They are shown in US-$$_{2005}$/t for hard coal and lignite, in US-$$_{2005}$/bbl for oil and in US-$$_{2005}$/1000Nm³ for natural gas. First, the results from the deterministic optimization are presented. As laid out, all stochastic parameters have been set to their MID case value for the deterministic calculation which is primarily a benchmark to analyze the impact of uncertainties. It should not be interpreted as a point forecast for fossil fuel prices. In a second step, the stochastic results are shown. A detailed discussion and analysis follow in the last section of the chapter.

7.3.1 Deterministic optimization results

Fig. 7-12 shows the deterministic results for crude oil and natural gas. From 2005 to 2020, prices remain about stable. They increase only by 0.8 percent and 0.6 percent annually, for oil and gas respectively.

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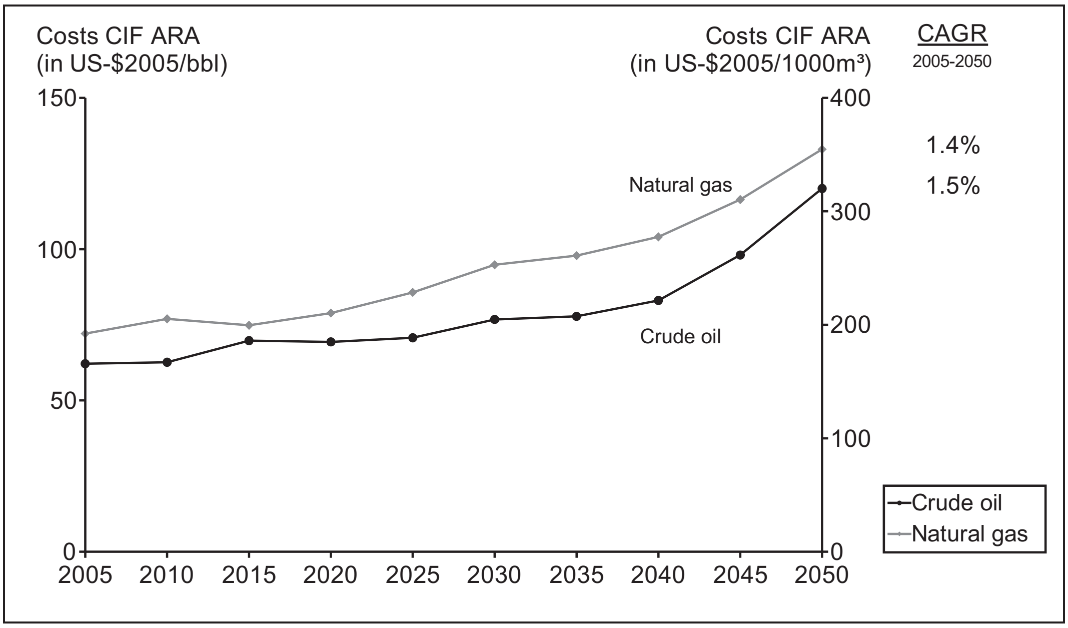
[100] Using a 2007 state-of-the-art desktop computer system (i.e. Pentium D CPU with 3 GHz and 2 GB RAM), a full model run (deterministic and stochastic) requires about 23 hours, not including time for data evaluation, preparation and analysis.

[101] Cf. section 6.4.



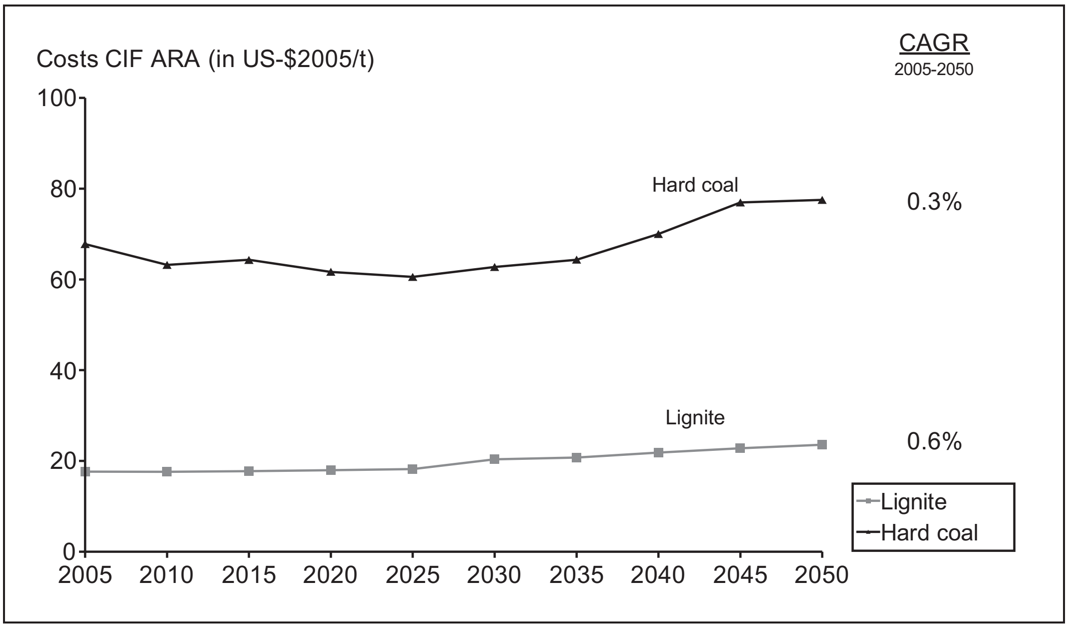
Source: Own representation
Note: CAGR = Compound Annual Growth Rate

Fig. 7-12: Deterministic results: Oil and gas

After 2020, prices start to grow substantially faster. Natural gas prices rise about 1.7 percent annually until 2050, oil prices 1.8 percent. Over the last ten years of the model horizon, i.e. from 2040 to 2050, the annual growth rates are even higher, namely 2.4 percent for natural gas and 3.8 percent for crude oil. This is probably due to an increase in scarcity. In 2050, the natural gas price reaches 350 US-$_{2005}$/1000Nm³, crude oil costs about 120 US-$_{2005}$/bbl.

Oil and gas prices seem to grow in line with each other even though a gas price indexation to oil is not explicitly included in the model. However, due to the good substitutability between the two fuels and the possibility of natural gas being converted into oil via liquefaction, this is not surprising. A statistical analysis of the correlation between oil and gas prices will be carried out for the stochastic results further below.

The deterministic results for hard coal and lignite are shown in Fig. 7-13.



Source: Own representation
Note: CAGR = Compound Annual Growth Rate

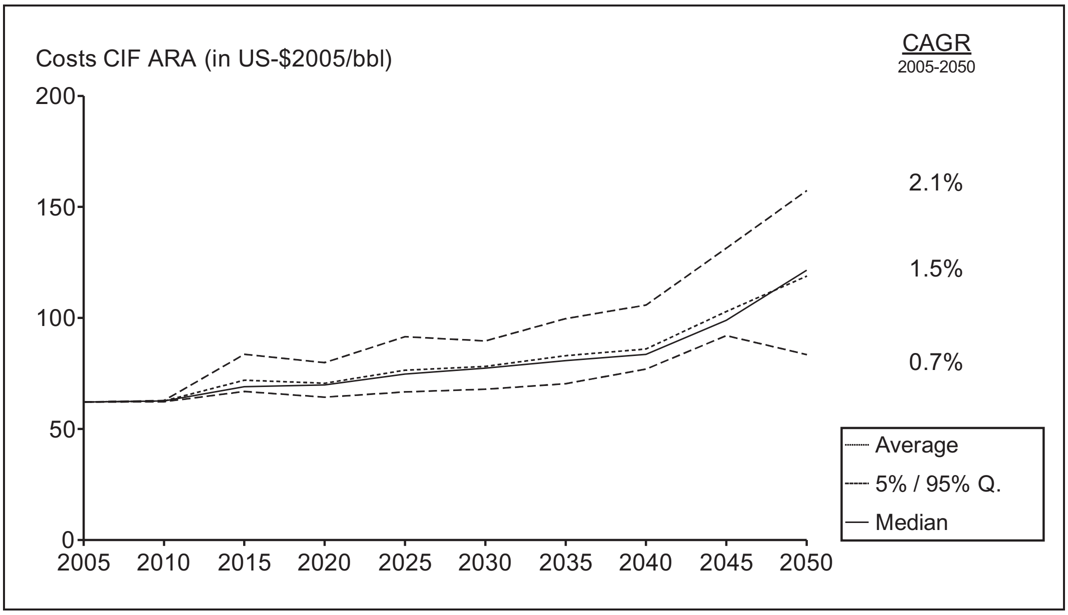
Fig. 7-13: Deterministic results: Hard coal and lignite

The price increases for hard coal and lignite are more moderate than for oil and gas. This is explained by the fact that depletion and increasing production costs are very unlikely to be a critical issue before 2050. Lignite prices remain constant until 2025 (0.2 percent annual growth rate), then rise about 1 percent annually until 2050. The higher growth rate after 2025 might be due to the increasing crude oil and natural gas prices, leading to a higher demand for long-term substitutes in power generation. Hard coal shows a small drop in prices until 2025, which is due to the modeling assumption that 2005 coal prices were above their long-term mean due to high demand especially in Asia. As capacities are being expanded, this effect will be alleviated slightly until 2025. However, this is probably only an insignificant effect, since the demand growth in Asia, especially in India and China, is expected to last. While hard coal prices remain about flat after the initial drop until 2035, the growth rate increases to about 1.3 percent in the period 2035 to 2050. Again, this can be explained by the increasing oil and gas prices, too. Also hard coal is increasingly used as substitute, especially for oil. High oil prices make the liquefaction process increasingly competitive, thus driving the global demand for hard coal and hard coal prices.

7.3.2 Stochastic modeling results

As described in subsection 7.1.6, the stochastic modeling is based on 200 randomly compiled scenarios. This means that for each price point shown in the deterministic results, now 200 data points are available which define the probable range of future price developments. Thus, all graphical representations of the stochastic price paths consist of four elements: the 5 percent and 95 percent quantile curves, shown as lower and upper dashed line, the median of the time series, shown as continuous line, and the price averages shown as dotted line.

Fig. 7-14 shows the stochastic results for crude oil, Fig. 7-15 compares stochastic and deterministic results.

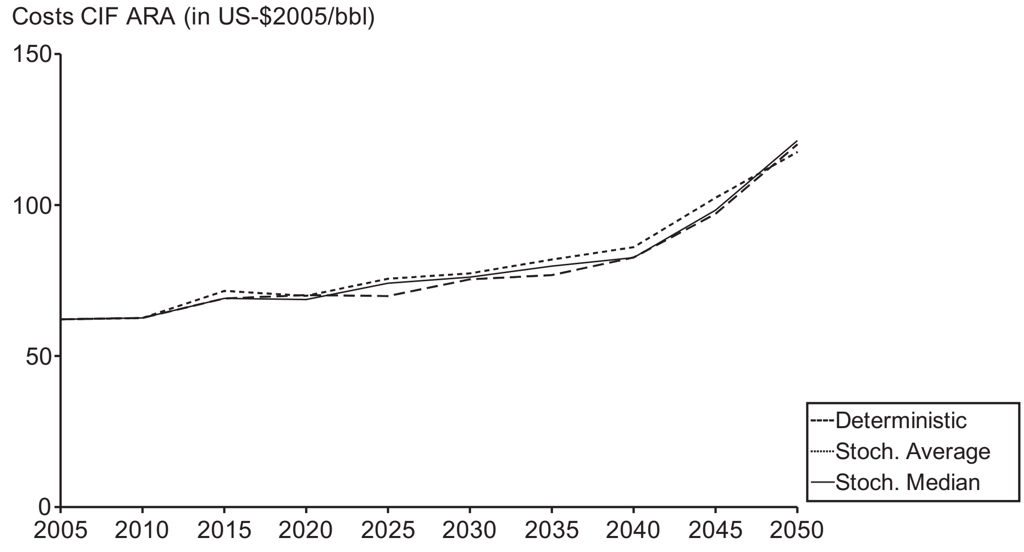


Source: Own representation
Note: CAGR = Compound Annual Growth Rate

Fig. 7-14: Stochastic results: Crude oil

In Fig. 7-14, the 95 percent quantile line is about 20 to 30 percent higher than the median value over the entire model horizon. The ability to convert hard coal and natural gas into oil via CTL and GTL technologies creates an upper boundary for the oil price level and prevents the occurrence of large price jumps. Still, it needs to be kept in mind, that these results reflect only fundamental data and do not incorporate other, e.g. political, uncertainties. The difference between median and 5 percent quantile however remains in the range of 10 to 15 percent in all periods, except for 2050. In this period, a sustained drop of the 5 percent quantile prices can be observed. This is driven by the scenarios where significant coal liquefaction facilities have been built up. Under these circumstances, a large share of the oil demand can be satisfied from converted hard coal, thus reducing the impact of increasing scarcity of conventional crude oil on prices.

In Fig. 7-15, the median price curve shows a development virtually identical to the deterministic results; also the average price curve is very similar to the median and the deterministic curves, as shown in Fig. 7-15. The fact that deterministic and mean values are nearly identical (maximum spread of about 5 US-$/bbl) indicates few chances for a significant and sustained drop in oil prices. This view is supported by the comparatively small difference between median and 5 percent quantile (cf. Fig. 7-14).

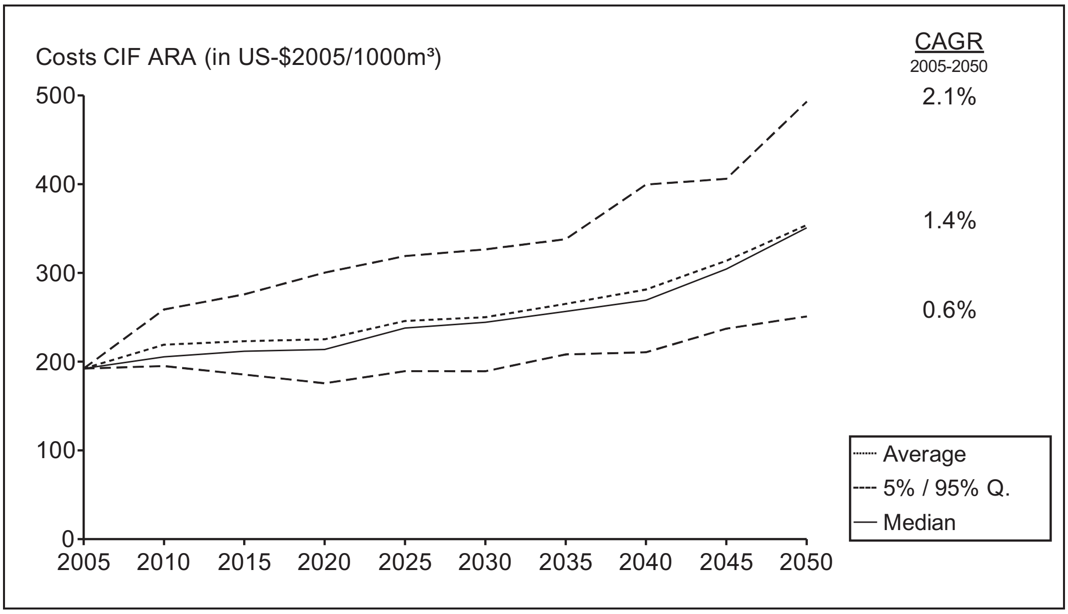


Source: Own representation

Fig. 7-15: Deterministic vs. stochastic results: Crude oil

Similar to crude oil, the 95 percent quantile line for natural gas (cf. Fig. 7-16) shows a markup in a range of about 25 to 40 percent over the entire model horizon. Regarding the development of the lower quantile line, it can be noticed that the percentage deviation from the median development is slightly higher than for crude oil, namely up to nearly 30 percent in the last period. In addition, the 5 percent quantile shows nearly a flat development with only 0.6 percent annual growth over the entire model horizon.

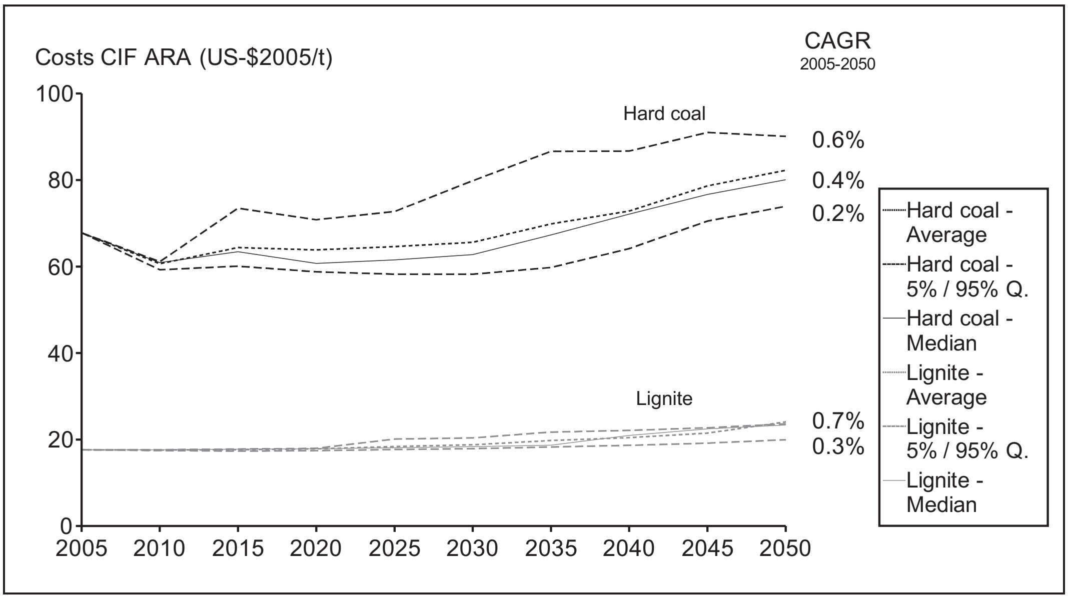
Average and median price curve are almost identical over the modeling period. Obviously, model uncertainty is primarily reflected in the results by the spread between 5 percent and 95 percent quantile and not by the development of the median values.



Source: Own representation
Note: CAGR = Compound Annual Growth Rate

Fig. 7-16: Stochastic results: Natural gas

Stochastic results for hard coal and lignite prices are shown in Fig. 7-17:



Source: Own representation
Note: CAGR = Compound Annual Growth Rate

Fig. 7-17: Stochastic results: Hard coal and lignite

Not surprisingly, hard coal and lignite prices are much less affected by the uncertainties in the model. It should be remembered that reserves figures for these two fossil fuels are implemented as deterministic parameters and are thus not subject to random adjustments. Implementing stochastic reserve figures would probably increase the spread between 5 percent and 95 percent quantiles.

Currently, especially lignite does not show much price dynamics over time nor between the different price curves. This seems quite reasonable as lignite is primarily a local business and is thus not directly affected by geopolitical events. In addition, the model allows the usage of lignite only in power generation, the demand sector with the longest equipment lifetime and consequently with the highest predictability once an investment has been made. The biggest threat for lignite production is in fact the uncertain development of CO_2 emission costs. However, this will probably impact production volumes much more than production costs and thus prices.

Hard coal shows a more distinctive response to the uncertainties. There are several possible approaches to explain that: First, hard coal has a better versatility compared to lignite. In addition to power generation, it can be used to produce industrial heat, too. It is also still being used for domestic heating. Therefore, the chances of being a substitute fuel to oil and gas is higher than for lignite. Thus, the correlation to price trends in oil and gas should be higher, too. Second, hard coal is also a direct substitute for oil through the coal liquefaction process.

7.4 Analysis and verification of results

A general verification of the model and its results has been carried out continuously by applying the methods described in section 6.4. To further test the validity and plausibility of the results described above, several additional analyses are conducted[102]. In particular, the results are tested for leptokurtosis, i.e. the existence of fat tails, which is composed of tests of skewness und kurtosis.

Also, it should be expected that prices of crude oil and natural gas are closely correlated to each other due to the good inter-substitutability and the oil price indexation for natural gas, especially in Europe. To test whether this is reflected in the model or not, the results of the 200 scenarios are examined for correlation

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[102] Another methodology to test the model would be a sensitivity test. However, this is not carried out for the following reason: Based on the discussion of key drivers on prices in the chapters 4 and 5, the most important factors are implemented stochastically, i.e. they already assume different values over the multiple model runs. Thus, the sensitivity test is effectively already included in the model and a further variation of these model parameters would not create additional insights.

between oil and gas prices. Third, the results are compared with the results of other studies that have been introduced in section 6.6.

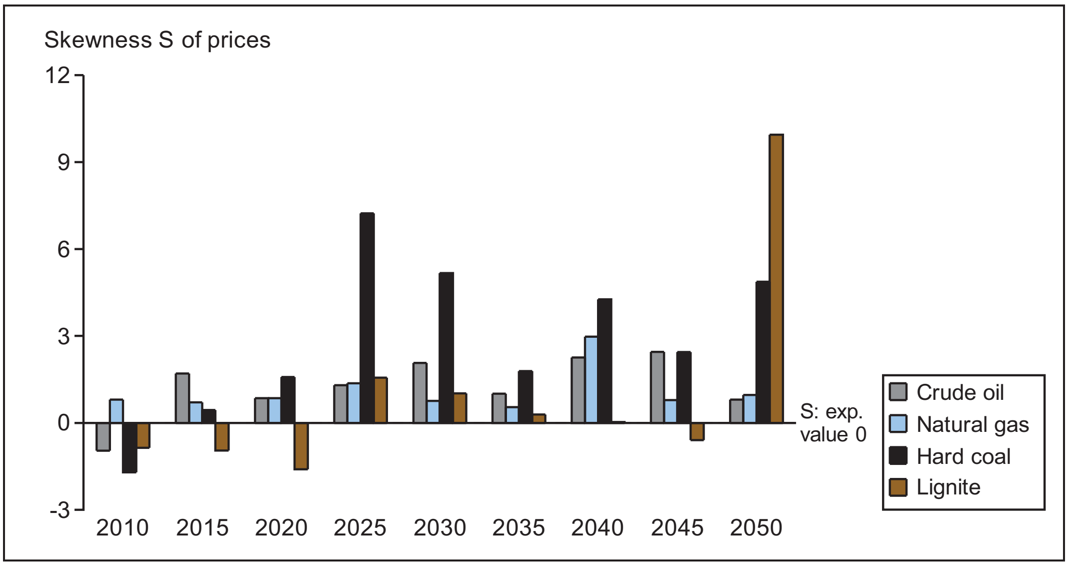
7.4.1 Distribution of results

As discussed above, the difference between 95 percent quantile prices and average or median values seems to be bigger than the difference between 5 percent quantiles and average or median values. This is an indication for a right-skewed distribution of results, i.e. upward deviations occur more frequently than downward deviations. However, average and median values are always nearly identical, which is contradictory to the existence of a significant skewness.

The results are tested for symmetrical Gaussian distribution. The validation of this assumption would reject the existence of any fat tails in the results. For that purpose, a Jarque-Bera test (cf. equation 6.10) is applied. The χ_2^2 threshold value at a probability of error of 5 percent is calculated to 5.991 (cf. Poddig, Dichtl et al. 2003, p. 766). To prove a symmetric Gaussian distribution, the results from equation (6.10) must be smaller than this threshold. It can be shown that for each fossil fuel and each period, the Jarque-Bera test of the 200 individual prices (i.e. from the 200 stochastic optimizations) leads to a clear rejection of the null hypothesis of a symmetric Gaussian distribution. Thus, the existence of fat tails can not be disproved in this first step.

For more detailed insights, both skewness *S* and kurtosis *K* of each fuel and period are considered separately. As explained in subsection 6.3.4, a positive value for *S* indicates a right-skewed distribution of results, whereas a negative value means a left-skewed distribution. For *K*, a value above 3 means that the variance is primarily driven by the existence of few but extreme deviations (leptokurtosis, cf. Poddig, Dichtl et al. 2003, p. 143). A value below 3 points towards a small variance with homogenous results (platykurtosis).

Fig. 7-18 shows the results for the skewness of the stochastic results for prices from 2010 to 2050. With the exception of primarily lignite in the some periods, the results are always skewed to the right.



Source: Own representation

Fig. 7-18: Stochastic results: Skewness of results from 200 scenarios

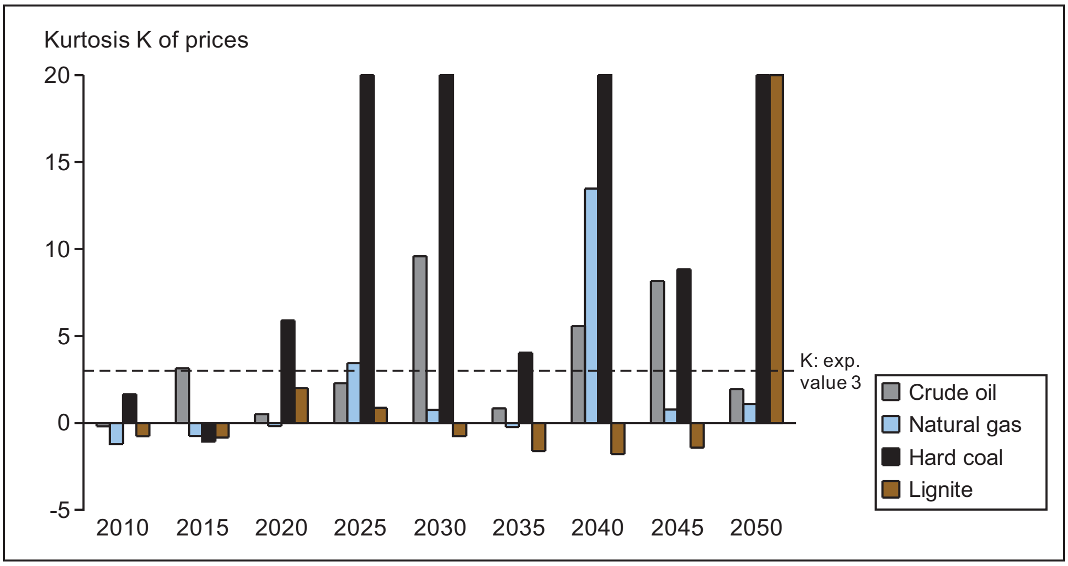
The general trend to right-skewed results is most likely not due to unwanted biased model behavior or input data. Looking at the model equations and the stochastic extension, there is no pattern that would explain such a trend. The data for the stochastic parameters would rather suggest left-skewed results because the MID case is based on rather conservative assumptions. For final energy demand, the percental deviation of the LOW case (assuming a lower demand) is triple as high as for the HIGH case. For CO_2 emissions, costs fall 100 percent in the LOW case but can increase only by 60 to 70 percent in most periods in the HIGH case. For natural gas, the difference in fuel availability (cf. Tab. 7-3) between HIGH and MID case is substantially higher than between MID and LOW case. Crude oil in fact is the only one of the four stochastic parameters where the value for the MID case is slightly higher than the midpoint between LOW and HIGH case. This could explain right-skewed results to a certain degree. However, it could be expected that the impact of the three other stochastic parameters would at least compensate for this effect. Thus, there must be other reasons for the right-skewed results that cannot be attributed to misspecifications of the model setup and skewed input data but have rather economical reasons.

Most strikingly, the skewness for hard coal after 2020 and for lignite in the last period takes very high values. In other words, the prices in these periods are distributed very asymmetrically, i.e. are much more likely to deviate upwards from their average and median values than downwards. This is probably due to the fact that hard coal is extremely sought after in some scenarios when crude oil suddenly becomes scarce and expensive. Using coal liquefaction techniques, hard coal is brought in as substitute fuel, thus extremely driving the demand which leads to higher production costs, more investments in production capacities and an increase in imports from distant regions to Europe, in sum leading to substantial price spikes. Ultimately, the high demand for hard coal also leads to a search for substitutes in demand sectors where crude oil does not play a relevant role. In other words, as hard coal is increasingly used as crude oil replacement, the electricity sector sharply switches from hard coal to lignite in some stochastic scenarios, leading to the high skewness value in the last period.

In Fig. 7-18, the distributions of results for crude oil show a consistent skewness to the right after 2010 but unlike hard coal without a large increase in skewness in the last periods. This can be explained by the fact that if crude oil prices exceed the threshold price that makes large-scale coal liquefaction economically viable, the model will seek to satisfy crude oil demand as much as possible from coal liquefaction (provided that CO_2 emission costs are not to high) because scarcity is much less an issue for hard coal than for crude oil. Thus, once oil prices have reached this threshold price they are not likely to increase much further and extreme price spikes do not occur that often.

For natural gas prices, skewness is consistently low in the periods until 2035. It is only in 2040 that skewness increases significantly although it does not reach the dimensions of hard coal and lignite. In the early periods, natural gas scarcity is not a major issue in any scenario. But when in some scenarios crude oil becomes scarce and expensive, natural gas – like hard coal and indirectly lignite as well – becomes increasingly sought after as substitute fuel and for liquefaction purposes. However, as the model assumes gas liquefaction to occur in the regions of gas production and hence most likely outside Western Europe, the impact on natural gas prices is somewhat lessened, resulting in a lower number of price spikes within the 200 scenarios and thus a lower skewness value.

The development of the kurtosis of the price results per fuel and per period is shown in Fig. 7-19. Again, hard coal and lignite display the most eye-catching results with extremely high values for K (>20). Also, the distribution of natural gas prices comes with a kurtosis of about 13 in 2040.

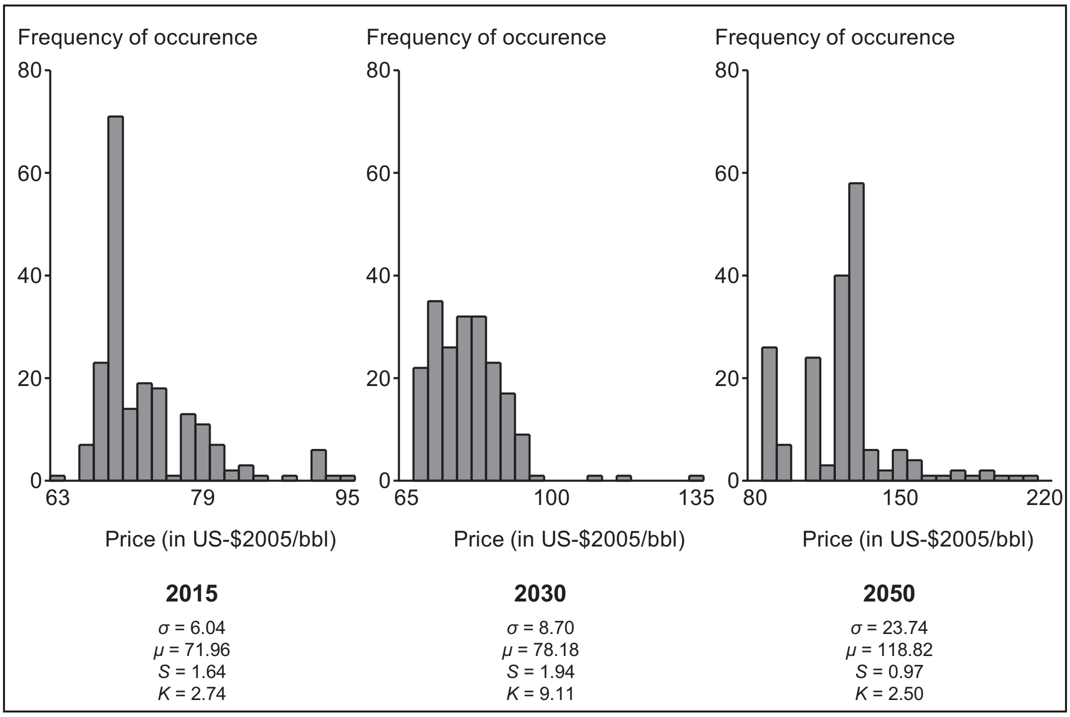


Source: Own representation

Fig. 7-19: Stochastic results: Kurtosis of results from 200 scenarios

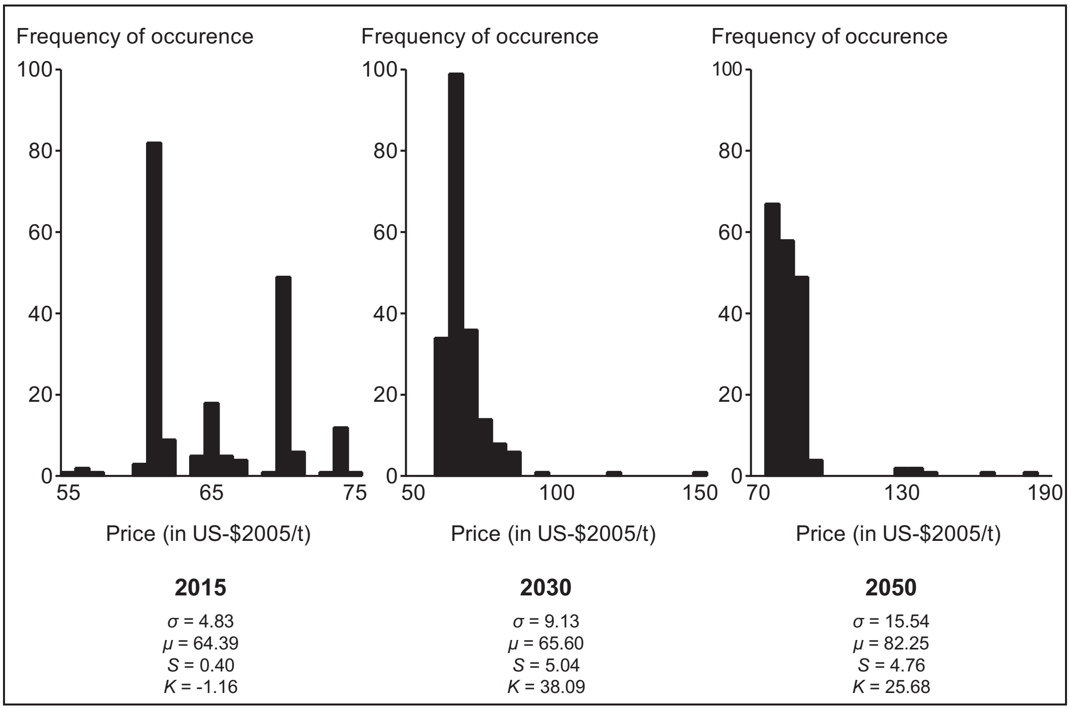
The same economical explanations as provided for the occurrence of right-skewed results above are applicable here, too. Particularly hard coal prices seem to experience significant price jumps in some scenarios. Again, this can be due to the fact that directly and indirectly (via liquefaction or as substitute for oil substitute fuels in the case of lignite) the demand for all non-oil fuels may increase dramatically and unexpectedly in same rare cases when crude oil suddenly becomes scarce and expensive. Also in these cases, the oil price itself does not increase too much but remains just high enough to make the substitute fuels from coal and gas liquefaction competitive.

For a better illustration, the distribution of prices for crude oil and hard coal are compared in Fig. 7-20 and Fig. 7-21 for the periods 2015, 2030 and 2050. Each graph shows the distribution of prices, i.e. single price points and their frequency of occurrence as well as the standard deviation, mean, skewness and kurtosis of the respective distribution.



Source: Own representation

Fig. 7-20: Distributions of crude oil price results in 2015, 2030 and 2050



Source: Own representation

Fig. 7-21: Distributions of hard coal price results in 2015, 2030 and 2050

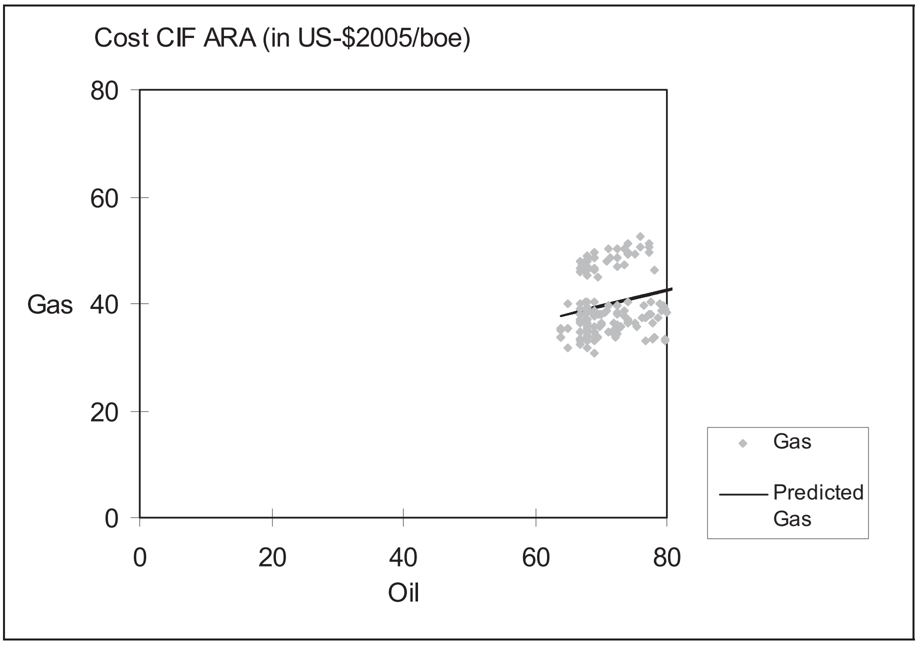
In Fig. 7-20, the distributions in 2015 and 2030 show the difference between skewness and kurtosis. In 2015, oil prices are clearly skewed to the right with $S = 1.64$ and a slight platykurtosis with $K = 2.74$. In the graph, the existence of a fat tail on the right-hand side is visible. In 2030, K has a much higher value, indicating a clear leptokurtosis. The existence of fat tails is obvious again as some price spikes occur. In 2050, the skewness of the results is observed again. More than three fourths of the price points are located between 80 and 130 US-$\$_{2005}$/bbl, the remaining results being spread between 130 and 220 US-$\$_{2005}$/bbl.

The corresponding graph for hard coal prices in 2050 in Fig. 7-21 shows a similar shape with the majority of price points in the lower range and some few extreme price spikes which occur in the same scenarios as the spikes in oil prices. For the periods 2015 and 2030, the range of hard coal prices is much smaller than in 2050, similar to the crude oil prices.

In summary, it can be concluded that for the majority of fuels and periods the distribution of prices is clearly right-skewed. In addition, as the comparison for crude oil and hard coal has shown, skewness occurs simultaneously for different fuels. In real world conditions, such a behavior of the results would be expected based on the degree of substitutability between different fuels. Thus, it can be shown that even the limitation to fundamental key drivers in the model can lead to price spikes in long-term fuel prices, solely due to the myopic behavior of market participants and their misinterpretation of future developments in some occasions.

7.4.2 Correlation of oil and gas prices

Regarding the correlation of oil and gas prices, again three representative periods (2015, 2030 and 2050) are tested. Oil price is taken as explanatory variable and gas price as dependent variable. To allow a meaningful comparison, gas prices are converted from \$/1000Nm^3 to \$/boe (barrel of oil equivalent). Fig. 7-22 shows for 2015 that a correlation exists (regression coefficient of 0.2946) and that the correlation is statistically significant (t-test value of 4.363).



Source: Own representation

Fig. 7-22: Correlation of stochastic oil and gas prices in 2015

For the periods 2030 and 2050, the regression analyses yield similar results (cf. Tab. 7-9). Thus, it can be concluded that, even though not explicitly implemented in the model, crude oil and natural gas show very similar patterns of price formation.

	Adjusted R²	**Correlation coefficient**
2030	0.5742	0.6756
2050	0.6807	0.4644

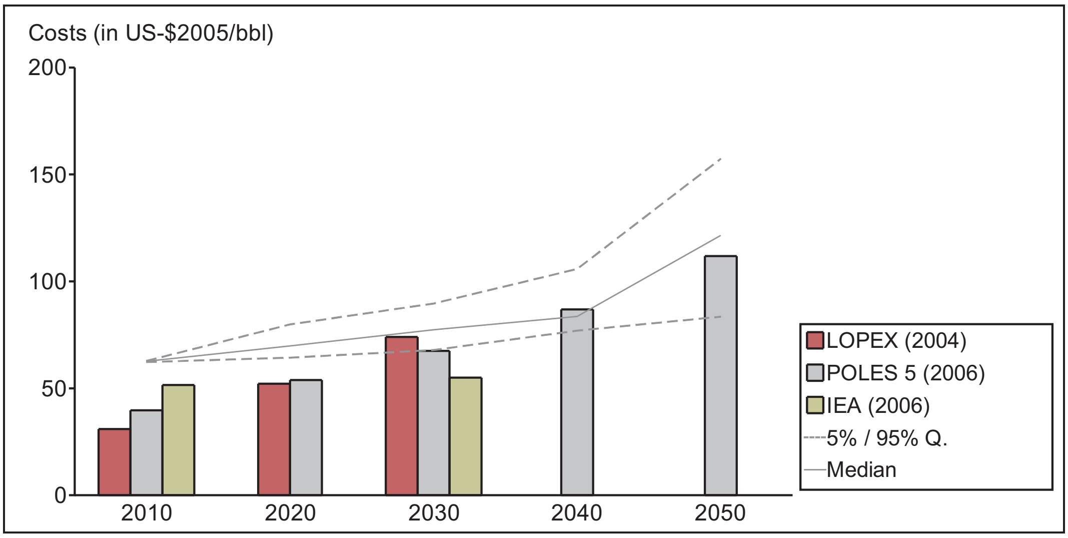
Source: Own representation

Tab. 7-9: Correlation for oil and gas prices in 2030 and 2050

7.4.3 Comparison with results from other fuel price models

Comparing the results of the newly developed model with prices from other models (cf. section 6.4), the findings slightly deviate from each other for crude oil and natural gas. Fig. 7-23 shows the comparison with the results from Rehrl and Friedrich (2006), i.e LOPEX, LEPII-EPE (2006b), i.e. POLES 5, as well as IEA

(2006). Results from other models are shown as bars, results from the own model are depicted as lines (median, 5 percent and 95 percent quantiles shown).

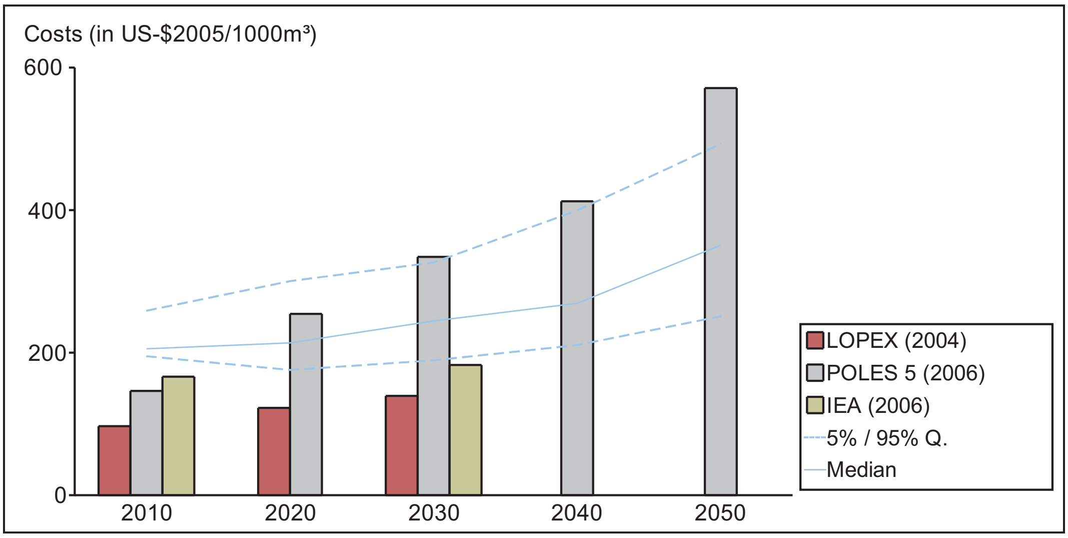


Source: Own representation

Fig. 7-23: Comparison with other model results: Crude oil

Before 2030, the range of prices calculated in this thesis is higher than the results from the other studies. This is probably due to the adjustment of model input data to reflect the observed high prices in 2005. Beyond 2030, only data from the POLES reference case is available. For 2040, POLES reference case forecast and own median are nearly identical. The 95 percent quantile of prices is some 30 percent higher than the POLES forecast. From 2040 to 2050, prices of the own model outgrow the POLES price slightly so that the median price exceeds the POLES value (112 US-$/bbl) by nearly ten percent, the 95 percent quantile even by 40 percent.

For natural gas, the comparison looks different, in particular with regard to the POLES results (cf. Fig. 7-24). Leaving aside the POLES prices, the range of own natural gas prices lies considerably above the results of the other models. Again, this is primarily due to the fact that the own model is calibrated to a 2005 price level around 200 US-$/1000Nm³ for natural gas supplied to Europe, based on recent price points from e.g. Gazprom (cf. e.g. Aslund and Karatnycky 2005) and the discussion of a possible *Gas OPEC* (cf. e.g. Itar-Tass 2007). Also, it should be noted that the LOPEX model applies a different interest rate for its gas section (5 percent) than for its oil section where 7.5 percent are applied (cf. Fahl, Bickel et al. 2004, pp. 48 and 62). This might lead to comparatively low gas price estimates, if capital costs are not priced in appropriately.



Source: Own representation

Fig. 7-24: Comparison with other model results: Natural gas

As discussed in section 6.6 already, the POLES prices for natural gas are very high compared to other studies, probably due to a very tight interrelation to oil prices. Compared with the results, POLES gas prices of the reference case even exceed the 95 percent quantile of the results.

7.5 Summary and implications for decision makers

As the above tests have shown, the results from the model are both plausible and of statistical significance. In the following, the implications from these results are discussed.

Overall, it can be concluded that hard coal and lignite prices are likely to increase significantly slower than prices for crude oil and natural gas. While hard coal and lignite median prices show moderate annual growth rates clearly below 1 percent, the price increases for natural gas and most notably crude oil are in the range of 1.5 percent p.a. for the median. In 2050, the calculated price corridor for crude oil ranges from 80 $/bbl to 160 $/bbl (with a median of 120 $/bbl) and for natural gas from 250 $/1000Nm³ to 490 $/1000Nm³ (median of 350 $/1000Nm³). This is mirrored by a range of prices from 72 to 90 $/t for hard coal and from 21 to 25 $/t for lignite. The fact that the corridor of results is much wider for crude oil and natural gas can be interpreted in a way that prices of these fuels have a higher volatility and thus are a more relevant source of risk and uncertainty than hard coal and lignite. This coincides with the current prevailing perception that depletion is primarily an issue for crude oil and, to some extent, for natural gas whereas there are ample reserves of hard coal and lignite.

The fact that the median of prices is in general closer to the 5 percent quantile than to the 95 percent quantile in nearly every period for all fuels indicates that in most of the 200 scenarios a comparatively moderate price increase takes place. However, several scenarios exist in which considerable price spikes occur. For decision makers, this means that if they base their judgment on current expectations, i.e. assume a development in the magnitude of average and median prices, they are likely to do well with a reasonable probability. However, as the right-skewed results prove, there are some situations in which the decision makers can be negatively surprised by very high price jumps. Taken one step further, this can mean that expenditures for costly back-up options, i.e. reserve plants fired by different fuels or the ability of a plant to switch between fuels, will in the majority of cases not pay off. Yet if they are incurred, they may avoid extreme price shocks in some cases.

The danger of price spikes seems to be particularly high in the last periods. Since the model only includes fundamental data, this can only be due to scenarios characterized by low reserves volumes, i.e. where the model is forced to resort to expensive non-conventional reserves on a large scale. For the further analysis of the occurrence of price spikes, it might be rewarding to include political events and uncertainties in the model[103]. Still, as political circumstances can change quickly and abruptly (other than fundamental parameters), it is questionable whether it makes sense at all to include them in models covering several decades.

Also, the price increases in the last periods can be partially due to the application of a residual value of in-situ volumes at the end of the model horizon. The residual value is based on the assumption that especially crude oil and natural gas remain valuable natural resources long after 2050. The possibility of a backstop technology is not considered explicitly. However, already the prospect of the introduction of a backstop technology can lead to significantly lower prices, as section 5.1 has shown.

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[103] This could be done e.g. by stochastically reducing the supply volumes from selected regions temporarily. However, to come to meaningful results, intensive data research on probabilities and extent of such events is required.

The introduction of a backstop technology is not considered in the current model yet. Still, it may not be that far off that in 2035 or 2040 the introduction of e.g. nuclear fusion is expected 20 to 30 years later. Countries that heavily depend on oil and gas exports will reduce their cartel behavior which is currently included in the above results, at least rudimentarily. Thus, it seems possible that the price increase in the last periods turns out to be less drastic than shown here. Still, these are issues that are probably some decades away.

Both political and private entities should continue to reduce their dependency on oil and gas products. This can be achieved by diversifying fossil fuels and fuel suppliers as much as possible (cf. subsection 5.2.5). Also, the reduction of total demand and the substitution with non-fossil fuels (cf. subsection 5.2.3) will continue to play an important role. This way, the negative impact from probable fuel price shocks on the European economy and households can be mitigated. The benefits of such policies are already visible today: The current situation, i.e. considerable economic growth despite very high oil prices, shows that the dependency on crude oil has declined substantially since the oil crises in the 1970s. For Germany, the GDP energy intensity has fallen by 43 percent from 1973 to 2007 (cf. Spiegel Online 2007). In addition, the strong Euro is currently able to mitigate negative effects from high oil prices, traditionally settled in U.S. dollars.

Also, decision makers should try to benefit from the moderate price increases and stable supply situation for hard coal and lignite. As these fuels carry the stigma of significantly driving the global warming, technologies for sequestration and storage of CO_2 (CCS) need to be developed to exploit the advantages of these energy sources. With regard to the approach developed in this thesis, it might be rewarding to include CCS technologies into the model to see how this affects the advantageousness of CO_2-intense fuels.

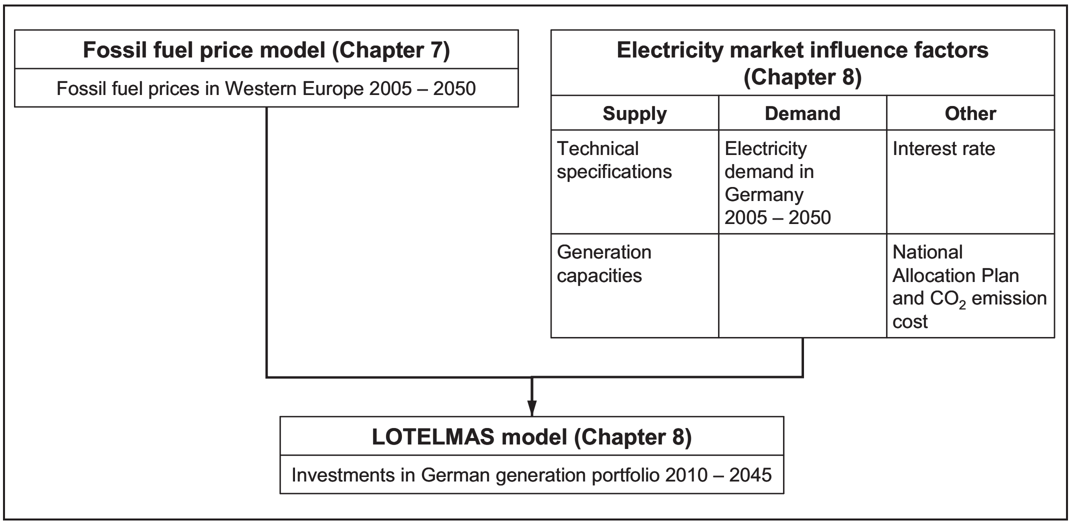
Although the large-scale deployment of a backstop technology seems to be far away from today's perspective, it seems reasonable to conclude that the age of fossil fuels is likely to come to an end within the second half of this century. This will probably happen as a gradual shift to other energy sources and will be primarily driven by increasing prices and improving competitiveness of alternative technologies as well as by efforts to mitigate global warming effects. Considering the results of this thesis, it seems unlikely that the shift away from fossil fuels will happen abruptly, due to sudden and unexpected depletion of fuel reserves. Thus, depletion and the end of the oil age do not play a major role for today's investment decisions.

Still, the example of use in the next chapter will show that the consideration of uncertainties in fossil fuel prices and thus the results of this thesis can make a significant difference when it comes to the choice of the adequate fuel in power generation.

8 APPLICATION OF MODEL RESULTS: INVESTMENTS IN POWER GENERATION

Projections of the future fuel price range are not only of academic interest but also have economic implications, e.g. for optimal investments in power plant capacities. Based on the model described in the previous chapter, planners can adjust the underlying assumptions according to their own expectations and can expand the model with any quantifiable uncertainty of their choice.

To come to meaningful results about future developments in the German generation portfolio, the results of the fossil fuel price model are fed into a second optimization model developed by Weber (2005b) that simultaneously considers future electricity prices and investment in generation capacities. The data flow between the two models is illustrated in Fig. 8-1.



Supply	**Demand**	**Other**
Technical specifications	Electricity demand in Germany 2005 – 2050	Interest rate
Generation capacities		National Allocation Plan and CO_2 emission cost

Source: Own representation

Fig. 8-1: Data flow between fossil fuel price and electricity market models

In the first section of this chapter, the general structure of the model for capacity investments is introduced. Also, the modifications made to apply the newly calculated fossil fuel prices are presented. In the second section, the resulting capacity investments are discussed.

8.1 Forecasting capacity developments in the German electricity market

8.1.1 Description of the LOTELMAS model

The model LOTELMAS (**Lo**ng **T**erm **El**ectricity **Ma**rket **S**imulation) is described in detail in Weber and Swider (2004) and Weber (2005b). Therefore, only a brief introduction of the general setup and key functionalities is given here. For a thorough discussion of the underlying methodology and key data input, the interested reader is referred to one of the above publications.

LOTELMAS takes up the general ideas of the real options valuation described in subsection 3.2.2.3 and applies it to a dynamic partial equilibrium model of the German electricity market. It numerically models capacity investment decisions in an uncertain world. Fuel switching, uncertainties in fuel prices and CO_2 emissions costs as well as endogenously calculated output prices are considered simultaneously.

LOTELMAS is a stochastic linear optimization model implemented in GAMS. Its objective function is aimed at minimizing investment and operation costs required to cover a given electricity demand in Germany from 2005 to 2045. In detail, the cost function is comprised of operating costs for the current period plus investment costs for future capacities plus the probability-weighted sums of minimum costs of all subsequent periods. The key constraints include the bounds resulting from maximum capacities and loads as well as the future development of capacities based on the investments made. For the last period, final conditions have been defined, making that period a deterministic optimization problem.

The stochastic model works backwards through a scenario or decision tree. At each decision point, i.e. at each node on the decision tree, a two-stage optimization is carried out, consisting of the costs of the actual period, a detailed, probability-weighted account of the uncertain costs in the next period and a probability-weighted approximation of all further periods. In principle, an exact calculation of all further periods would be desirable, but this proves not to be feasible due to the complexity of the problem. Instead, an approximation technique known as *Benders cut* is applied in the second stage, calculating a lower barrier for future costs (cf. Weber 2005b, pp. 257 - 258).

The model horizon from 2005 to 2045 is covered in 5-year periods. The annual German load duration curve is represented by 144 segments. Based on the constantly flat development of electricity demand in Germany over the last decade[104], demand is assumed to remain constant over the entire modeling horizon. LOTELMAS includes technical features like startup costs and partial load efficiencies, hydro storage, minimum uptime and downtime durations. Technological and political uncertainties are not incorporated.

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[104] Less than 1 percent annual demand growth in Germany, cf. Weber (2005b), p. 260, and BDEW (2008), p. 23.

Due to their inability to provide base load generation, renewable technologies are not implemented as investment option in LOTELMAS. Instead, investments can be made in five conventional plant types: coal- and lignite-fired, gas turbine, gas combined cycle and nuclear. The latter can be excluded from the allowed investment alternatives to reflect impacts of the ongoing public discussion of nuclear generation. Each technology comes with different technical specifications, investment and operation costs. The interest rate is set to 7 percent.

In the original LOTELMAS version, fuels prices are determined by a combination of data from Deutscher Bundestag (2002) and a stochastic mean-reversion model for price growth rates (cf. Weber 2005b, pp. 57 - 60). The general long-term trend data is taken from the former source while the mean-reversion model is used to simulate short-term deviations from the trends. The fuel prices employed in LOTELMAS result from 1000 iterations of a Monte-Carlo simulation. The considerable broad price range for some fuels was part of the impetus to develop a more detailed forecast based on fundamental data.

8.1.2 Application of fossil fuel price series in LOTELMAS

The LOTELMAS model used for the application of fuel prices in this thesis is not identical with the version presented in Weber (2005b) any more. Over the last years, several modifications both in input data as well as in methodology have been made in order to keep the model up to date, reflecting technical and political developments. Since the LOTELMAS model is not the key focus of this thesis, only a rough overview on the most important changes is given. Tab. 8-1 shows the most important technical specifications of new power plant investment alternatives.

		Coal fired plant with atmospheric dust combustion	Lignite fired plant with atmospheric dust combustion	Gas turbine	Gas fired combined cycle plant
Net power output	MW	750	750	146	750
Overall fuel efficiency	%	46	43	38	58
Planning and construction time	a	5	2	2	4
Economic lifetime	a	40	40	30	30
Duration of decommissioning and deconstruction	a	0	0	0	0
Investment costs including site preparation costs and interest payments during construction phase	€/kW	1050	1200	350	550
Decommissioning and deconstruction cost	€/kW	38	38	38	38
Fixed operation costs	€/kW	44	13	11	20
Variable costs besides fuel costs	€/MWh	2.2	1.7	1.2	1.2

Source: Based on Weber (2005b), p. 263,
updated with new model assumptions

Tab. 8-1: Updated specifications of LOTELMAS investment alternatives

For CO_2 emission costs, the same assumptions as for the fossil fuel price model (cf. subsection 7.2.4) are applied to ensure consistency. In addition, the two German National Allocation Plans (NAP I and NAP II) are implemented. The NAPs set the CO_2 emission allowances for power plants and other CO_2 emitting facilities[105]. Multiplication with a compliance factor and the assumed annual full load hours per plant type (cf. BMU 2006, p. 54) yields the amount of free emission rights allocated to each plant, both in reality and in LOTELMAS. For the period beyond 2012, no compliance factors have been determined yet, so that an estimate had to be made. Tab. 8-2 shows the compliance factors implemented in the model. The decreasing compliance factor is expected be a key driver for replacements of old, carbon-intensive plants.

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[105] In NAP II, 750 g CO_2 per kWh net generation for coal-fired plants and 365 g CO_2 per kWh net generation for gaseous fuels, cf. BMU (2006), p. 52. For a discussion of allowance allocation rules discriminating between different primary fuels and technologies, refer to Weber, Vogel et al. (2008).

	Compliance factor
2005	97.55%
2010	85%
2015	60%
2020	35%

Source: BMU (2004), (2006)
and own estimates

Tab. 8-2: NAP compliance factors

For prices of oil, gas and hard coal, the median as well as 5 percent and 95 percent quantiles of the stochastic results shown in section 7.4 are converted into €/MWh$_{th}$ and transferred into LOTELMAS. Average transport costs within Germany are added to obtain prices at power plant. For lignite, only the median of the prices is transferred given that the uncertainty range is limited (cf. Fig. 7-17) and because LOTELMAS in the current version does not provide multiple scenarios for lignite prices.

8.2 Analysis and discussion of results

In this section, the results from the application of the fossil fuel price ranges in the LOTELMAS model are shown and discussed. Again, the deterministic results are presented first. They represent the optimal decisions in the absence of any uncertainties in fuel prices and other input parameters. Next, the probability-weighted results from the stochastic optimization are introduced which include all uncertainties included in the model.

The graphs with the model results show the new investments in the German generation portfolio, i.e. the investments required to replace old and costly plants. As the electricity demand is assumed to remain constant over the entire model horizon, all new plants are replacement facilities only and the total generation capacity is not increased[106]. Also, it should be noted that the results in Fig. 8-2 and Fig. 8-3 show cumulative numbers, i.e. the investments of all previous periods are included the results for a given year.

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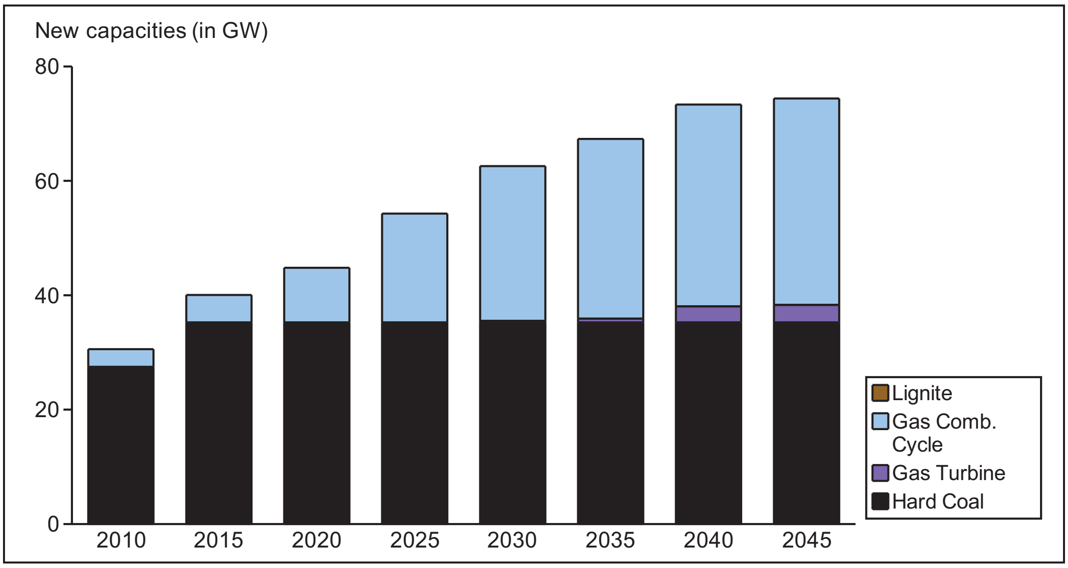
[106] In fact, some minor temporary changes in total generation capacities may occur but this is only due to different capacity utilizations of the different technologies, cf. Fig. 2-3.

The deterministic LOTELMAS results (cf. Fig. 8-2) show a clear preference for capital-intensive investments in the early periods. In 2010, about 27 GW of hard coal-fired generation capacity are installed. Capacities with lower capital costs, primarily gas-fired combined cycle plants are added only gradually until in 2040 each technology has a share of about 50 percent. In 2045, the deterministic calculation forecasts cumulated new capacities in the range of 36 GW for gas-fired combined cycle plants, 35 GW for hard-coal plants and a small share of gas turbines (about 3 GW). Lignite plants are not part of the deterministic optimum at all.



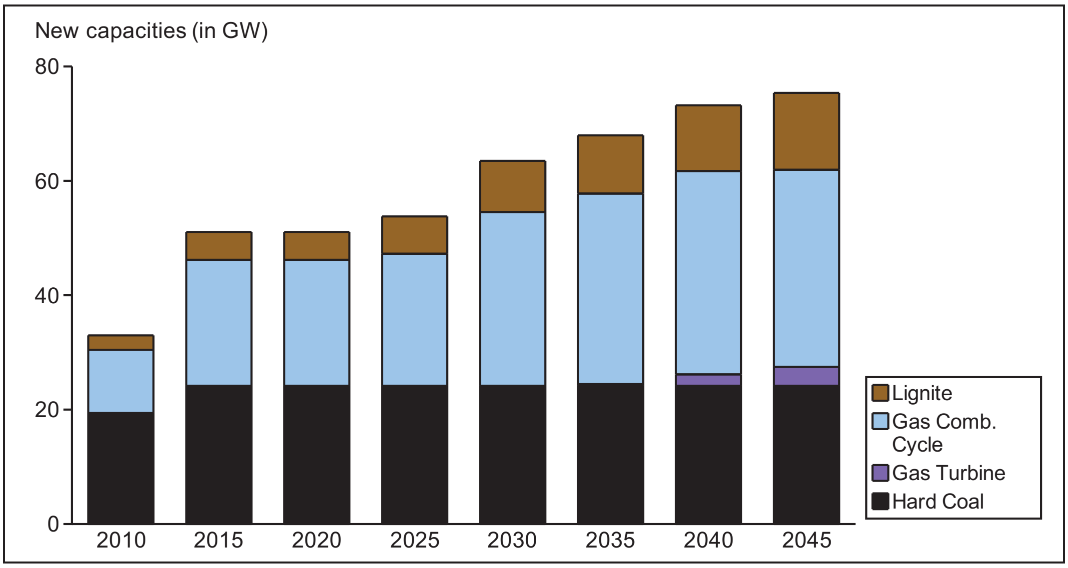
Source: Own representation

Fig. 8-2: Deterministic results: Capacity extensions

The high initial share of investments in capital-intensive technologies (in this case hard-coal fired plants) is due to the certainty that these plants will not be priced out of the market by a substantial and sustained drop in natural gas prices. Assuming the lack of any uncertainty, hard coal-fired plants will be definitely able to regain their high investment costs. But it is also certain that CO_2 emission costs rise over the entire model time span, making investments in lignite power plants unattractive and benefiting gas-fired plants at the same time. Another reason also driving investments in gas-fired capacities is their better applicability for medium and peak load generation, due to their shorter startup times. Especially for the latter case, also gas turbines with very high fuel costs are installed.

Looking at the probability-weighted results of the stochastic optimization in Fig. 8-3, the optimal solution has changed significantly. The investment in hard coal-fired plants is about two thirds of the deterministic solution, i.e. some 19 GW in

2010. In return, a small share of lignite-fired plants is built, amounting to about 2.5 GW in 2010 and then rising to more than 13 GW in 2045.



Source: Own representation

Fig. 8-3: Stochastic results: Capacity extensions

The fact that lignite-fired plants can become part of the optimal solution at all is due to the scenarios where CO_2 emission costs are at their lower bound. In this case, lignite plants would be more profitable than hard coal-fired plants in base load generation. For gas-fired plants, the inclusion of uncertain fuel prices proves to be a mixed blessing. On the one hand, gas-fired plants clearly benefit in scenarios with low gas prices and/ or high CO_2 emission costs. In such an environment, gas-fired generation will become highly competitive and might even replace hard coal and lignite in base load generation. On the other hand, gas-fired plants can easily become extremely costly to operate in cases where natural gas is in its upper range of prices. This effect would be worsened if CO_2 emission costs are low at the same time, further benefiting hard coal- and lignite-fired plants. Over the entire model horizon, the advantages and disadvantages level out approximately. The installed gas combined cycle capacities only differ by 2 GW in 2045 between the deterministic and the stochastic results. However, a distinction is clearly visible in the early periods: While in the deterministic optimization about 3 GW of gas-fired combined cycle plants is built until 2010, the stochastic results show 11 GW of capacity additions for this plant type in the same period. Also in 2015 and 2020, the cumulative investment in this plant type is significantly higher compared to the deterministic version, respectively. It is not before 2025 that the cumulative investment in gas-fired combined cycle plants has reached about the same level of magnitude in the deterministic and stochastic results. Thus, the findings of Dixit and Pindyck (1994) and Weber (2005b) are confirmed: The inclusion of uncertainties into investment decisions benefits less capital-intensive technologies because it becomes uncertain whether capital-intensive technologies will be able to regain their capital costs.

Gas turbines are only marginally affected by price uncertainties. As mentioned above, they are only used for peak load generation where they cannot be replaced by other technologies due to their short startup times. Thus, it can be said that they are required for technical reasons and costs only play a marginal role, especially given the mechanisms of peak load pricing.

As Weber (2005b) emphasized, not all investment decisions for the entire model horizon need to be made now. Only the results for 2010 and maybe 2015 should be of major interest, all other decisions can be postponed until better information on future developments becomes available. However, it could be shown in both models in chapters 7 and 8 that the inclusion of uncertainties also in the distant future significantly impacts (investment) decisions over the next couple of years. In the end, a balanced mix of technologies and fuel is likely to come close to the ex post optimal solution.

9 SUMMARY AND OUTLOOK

The liberalization of the electricity markets has made fuel prices one of the key factors driving generation portfolio planning of German utility companies. Price risks cannot be fully passed on to the customers any longer and power producers equipped with a disadvantageous set of power plants risk to be priced out of the market. Besides fuel prices, also CO_2 emission costs significantly impact the long-term profitability of generation technologies. The extremely long lifespan of power plants aggravates the difficulties of investment planning as it seems almost impossible to accurately forecast fuel prices and CO_2 emission costs over 30 or even 40 years.

However, the necessity of long-term investment decisions under uncertainty is not limited to power generation or the energy industry. Several approaches and methodologies have been developed that provide assistance in making such decisions. Some of them have been discussed in chapter 3. Particularly relevant for this thesis are scenario planning and the real options approach. In addition, myopic expectation formation plays an important role as well.

The fact that investment decisions in power generation are tightly knit with the future availability and prices of fossil fuels further complicates the situation. The assessment of future availability is an important driver of prices, if royalty rents are paid due to true or perceived scarcity. As chapter 4 has made clear, availability is the subject of heated debates in the scientific community with diametrically opposed views on future developments. One school of thought, referred to as Neo-Malthusians, regards the immediate depletion especially of oil and gas reserves as inevitable. Based on the peak oil theory, they argue that most of the reserves have been discovered already and that the current production level cannot be maintained over a longer period. Their opponents, known as Cornucopians, have a very different point of view. They argue that natural resources in general and fossil fuels in particular are virtually unboundedly available because the level of producible reserves is determined by market prices and sustained technological progress. The combination of higher prices and improved technology is expected to continuously open up mineral deposits for production that previously have been considered uneconomical. It is hardly possible to determine which side is right since both have their valid and plausible arguments. As the period under consideration is limited to 2050, it is assumed for the empirical part of this thesis that no fossil fuel will be depleted within this time span.

Relevant key drivers on the long-term formation of fossil fuel prices have been discussed in chapter 5. It turned out that the Hotelling rule, one of the prevalent concepts to explain fossil fuel prices, offers good explanations for some price patterns but fails to explain other phenomena. For example, assuming that scarcity actually is an important issue, the Hotelling rule explains how scarcity rent leads to continuously rising prices. Yet it has been shown that prices of natural resources can show a decrease over many years or even decades, contradicting the trend predicted by the Hotelling rule. It remains unclear whether this empirical observation is due to a superposition of effects that can all be fit into the Hotelling framework or if it invalidates the Hotelling rule. Furthermore, Hotelling's approach is very supply-oriented and does not include demand-driven effects like demand shocks or phenomena like market speculation.

In general, it can be said that fossil fuel prices are determined by a mixture of supply and demand related key drivers as well as other general parameters like geopolitical events or natural disasters. While the influence of each factor can be described qualitatively, it is nearly impossible to quantify the impact on prices, especially when considering the interrelations between different key drivers.

A key objective of this thesis has been to develop a numerical model able to incorporate uncertainties into the price formation process of fossil fuels. Hence, chapter 6 has sketched different modeling approaches and derived an appropriate methodology for this purpose. Based on the choice of an intertemporal linear optimization model with stochastic replanning, relevant techniques for this model type have been introduced with a particular focus on the introduction of stochastics into optimization models. The chapter also discusses three existing models providing reference values for the own results. Already in this comparison, it has become obvious that projection results differ significantly from model to model and from fuel to fuel.

Chapter 7 describes the empirical core of this thesis, i.e. the methodology chosen for the own model and the derived results. The developed methodology allows the modeling of fuel price uncertainty resulting from stochastic shocks in various fields based on fundamental data. It describes possible developments in a competitive market environment, where the market participants anticipate future scarcity and future technological and demand shifts. Yet they do not anticipate the full range of possible developments and consequently are repeatedly surprised by the occurrence of new stochastic shocks. These shocks have considerable and asymmetric impacts on the fuel prices, as shown by the model results. The distribution of fuel prices is in most cases right-skewed. This means that while in general decision makers would do well in basing their decisions on current expectations (reflected in the MID cases), the chance that they might be negatively surprised by fuel price developments should not be neglected. In some situations, a markup of up to 100 percent on current price expectations is conceivable. It should be kept in mind that these calculations are solely based on fundamental data and other key drivers like political uncertainties are not included yet. However, both structure and coding of the model allow for the addition of further uncertainties, provided that their probability of occurrence and their numerical impact can be quantified. Hence, the developed approach can be used as a basis to model the impact of stochastic shocks based on the specific assumptions of the respective decision maker.

The results are used as input for a second stochastic optimization model that analyses capacity investment in the German power sector. It turns out that for 2010, a high share of coal-fired plants (nearly 60 percent) and a share of gas-fired combined cycle plants in the magnitude of 30 percent is to be expected. The rest is covered by lignite-fired plants. After 2010, the largest share of capacity investments is made in gas-fired combined cycle plants.

Comparing these stochastic results to those of a deterministic optimization run, it becomes obvious that the existence of uncertainties has an impact on optimal investment decisions. Uncertainty benefits technologies with low investment costs (in this case gas-fired power plants) even though this type of plants are exposed to a higher fuel price risks. These results coincide with the findings of Dixit and Pindyck (1994) and Weber (2005b).

With regard to further research opportunities and needs, the fossil fuel model offers various possibilities for extensions. The most obvious enhancement is the addition of further uncertain, i.e. stochastically implemented parameters. Going beyond this rather simple enhancement, the probably most rewarding add-on would be to endogenize CO_2 emission costs. This would require information or assumptions regarding global, regional and sectoral emission limitations. In this context, interdependencies (i.e. substitution effects) with non-fossil fuels could be implemented that are currently only included as general elasticity of demand. In this context, also the sequestration and storage of CO_2 is an interesting field of research. The future attractiveness of CO_2-rich fossil fuels, i.e. hard coal and lignite, is likely to depend on the possibility of using them without worsening the global warming problem. Thus, an implementation in the model could provide valuable insights regarding the role of CCS technologies for the fuel mix of the future.

An aspect that has not been considered at all yet is the implementation of cartel power, especially in the oil market (cf. subsection 5.1.3). This influence is currently included in the production cost markup (cf. subsection 7.2.2 and constraint group IX in chapter 7). One possible approach to include cartelization effects into the model could be achieved by transforming the model into a MCP[107] approach, thus enabling the inclusion of market power in the model. As cartels are primarily relevant for crude oil, such an implementation might require splitting up the model in several sub-models, an approach e.g. applied in the LOPEX model (cf. subsection 6.6.2).

In summary, it can be concluded that fossil fuels will remain an essential and indispensable pillar of the global energy supply over the next decades. Despite the increasing efforts to mitigate the emission of greenhouse gases and the promotion of renewable energy sources, there are currently no technologies available to replace fossil fuels in the near- and mid-term future. All the more, it is important to evaluate future trends in fuel prices and availability, always keeping in mind that forecasts can only provide a probable range of developments and no exact predictions. All forecasts are highly subject to the underlying general attitude and assumptions, as illustrated by the discussions between Neo-Malthusians and Cornucopians. Hence, the model developed in this thesis should be regarded as tool to quantify the impact of various assumptions and inputs. The results shown in section 7.3 are thus only one instance of possible results, based on the assessments of the modeler. Different underlying assumptions may lead to substantially different results.

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[107] Mixed Complementary Problem. This technique allows to “accommodate market and game-theoretic equilibrium models which are not easily studied in an optimization context” (Rutherford 1995, p. 1300).

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