Band 28 _ PRODUKTION UND ENERGIE

Carmen Schiel

REAL OPTION BASED APPRAISAL OF ENVIRONMENTAL INVESTMENTS

AN ASSESSMENT OF NO_X EMISSION CONTROL TECHNIQUES IN LARGE COMBUSTION PLANTS

KIT Scientific Publishing

Carmen Schiel

Real Option Based Appraisal of Environmental Investments

An Assessment of NO_x Emission Control Techniques in Large Combustion Plants

PRODUKTION UND ENERGIE

Karlsruher Institut für Technologie (KIT)
Institut für Industriebetriebslehre und Industrielle Produktion
Deutsch-Französisches Institut für Umweltforschung

Band 28

Eine Übersicht aller bisher in dieser Schriftenreihe
erschienenen Bände finden Sie am Ende des Buches.

Real Option Based Appraisal of Environmental Investments

An Assessment of NO_x Emission Control Techniques in Large Combustion Plants

by
Carmen Schiel

KIT Scientific Publishing

Dissertation, Karlsruher Institut für Technologie
KIT-Fakultät für Wirtschaftswissenschaften

Tag der mündlichen Prüfung: 1. April 2019
Gutachter: Prof. Dr. Frank Schultmann, Prof. Dr. Michael Hiete

Impressum

KIT Scientific Publishing

Karlsruher Institut für Technologie (KIT)
KIT Scientific Publishing
Straße am Forum 2
D-76131 Karlsruhe

KIT Scientific Publishing is a registered trademark
of Karlsruhe Institute of Technology.
Reprint using the book cover is not allowed.

www.ksp.kit.edu

Print on Demand 2019 – Gedruckt auf FSC-zertifiziertem Papier

ISSN 2194-2404
ISBN 978-3-7315-0925-7
DOI 10.5445/KSP/1000093383

Real Option Based Appraisal of Environmental Investments

–

An Assessment of NO_X Emission Control Techniques in Large Combustion Plants

zur Erlangung des akademischen Grades eines

Doktors der Ingenieurwissenschaften

von der KIT-Fakultät für Wirtschaftswissenschaften
des Karlsruher Instituts für Technologie (KIT)

genehmigte

Dissertation

von

Carmen Schiel, M.Sc.

Tag der mündlichen Prüfung: 01. April 2019
Erster Gutachter: Prof. Dr. Frank Schultmann
Zweiter Gutachter: Prof. Dr. Michael Hiete

Acknowledgments

I would like to express my sincere gratitude towards all persons supporting this dissertation and my time as a research associate at KIT-IIP. In particular, I would like to thank my supervisor Prof. Frank Schultmann for his kind guidance, feedback, and confidence. Furthermore, I would like to thank Prof. Michael Hiete for supporting me as second examiner and Prof. Hagen Lindstädt and Prof. Melanie Schienle for being part of the board of examiners.

I gratefully acknowledge the work with the colleagues of CITEPA, ENEA, ADEME and UBA in the context of TFTEI, the Task Force on Techno-Economic Issues under the Convention on Long-range Transboundary Air Pollution. This work gave me the chance to gain insights into the field of environmental policy that I never expected to get. In particular the collaboration with Nadine Allemand, Jean-Guy Bartaire, Tiziano Pignatelli and Katja Kraus during the numerous meetings and with regard to various subjects was not only fruitful but always a pleasure and inspired my dissertation substantially. Furthermore, I would like to thank Simon Schulte Beerbühl and Ann-Kathrin Müller for their initiative to develop ERICCa_LCP and to Julian Huber for his great support during the first years of my time at IIP.

Moreover, I thank Magnus, Patrick, Sophia and Simon, the leaders of my research group 'Sustainable Supply Chains' who contributed with numerous helpful suggestions to the success of this work. I would also like to thank my colleagues for their constant motivation and support. Ann-Kathrin, Katrin, Sascha, and Kira shall be mentioned here representatively for the whole IIP-team. Finally and personally, my thanks go to my husband Philipp, my family and friends for their unceasing understanding and support.

Karlsruhe, April 2019 *Carmen Schiel*

Abstract

The thesis at hand provides a real option based decision support model for politically enforced environmental investments, which do not gain company internal economic profit. Therefore, a detailed methodology for the estimation of investments and operating costs for the exemplary application of NO_X emission control techniques in fossil-fueled large combustion plants is developed. This methodology focusses on the predominantly used secondary abatement techniques SCR (selective catalytic reduction) and SNCR (selective non-catalytic reduction). The results thereof serve as input values for a Monte-Carlo based real option model that investigates the influence of different policy instruments on the optimal timing of the investment. In focus are those policy instruments that provide an economic incentive for early investments such as investment funding schemes or emission fees.

The basic idea of real option theory is to consider the monetary value of future flexibility during investment decision-making. In the given context, investments without economic profit for the investor can be expected to be delayed as much as legally feasible. If, however, increasing expenditures for the same investment in future periods are likely, it may be profitable to advance the investment. In this case, future flexibility is lost, because the investment needs to be regarded as irreversible due to its technical complexity. Yet, at the same time, the risk that results from uncertain future developments is reduced or avoided. This decision situation is reflected by the model and analyzed for several exemplary case studies and scenarios.

The primary aim of this work is to develop a suitable calculation methodology for the application at hand. Nevertheless, the results of the case studies for a plant in the EU and in India reveal a general need for disruptive settings in order to cause an influence on the decision, i.e. an advancement of the investment. Policy instruments such as emission fees that lead to increasing expenditures for companies have in this context a stronger influence on the investment decision than nonrecurring investment-related funding schemes. An increase in future investment expenditures that is caused by market developments only can, within a reasonable scale, not be expected to cause an advanced investment.

Kurzfassung

Die vorliegende Dissertation befasst sich mit einem realoptionsbasierten Entscheidungsunterstützungsmodell für Umweltschutzinvestitionen, welche keinen innerbetrieblichen ökonomischen Nutzen erzielen, sondern durch entsprechende Gesetzgebung erzwungen werden. Dazu wird für den beispielhaften Fall von Emissionsminderungstechniken zur Reduktion von Stickoxiden in fossil befeuerten Großkraftwerken zunächst eine detaillierte Methodik zur Schätzung von Investitionen und Betriebskosten solcher Anlagen erarbeitet. Diese Methodik konzentriert sich auf die meistverwendeten sekundären Techniken SCR (selektive katalytische Reduktion) und SNCR (selektive nicht-katalytische Reduktion). Die Ergebnisse werden anschließend in ein Monte-Carlo basiertes Realoptionsmodell eingespeist, welches den Einfluss verschiedener politischer Instrumente auf den optimalen Zeitpunkt der Investition untersucht. Dabei werden insbesondere solche Instrumente betrachtet, die einen ökonomischen Anreiz zur frühzeitigen Investition bieten, wie etwa Investitionsförderprogramme oder Emissionsabgaben.

Die Grundidee der Realoptionstheorie ist es, den Wert zukünftiger Flexibilität in eine unternehmerische Entscheidung mit einzupreisen. Im gegebenen Fall kann davon ausgegangen werden, dass Investitionen ohne ökonomischen Nutzen für den Investor soweit rechtlich zulässig in die Zukunft verschoben werden. Falls jedoch in Zukunft mit steigenden Ausgaben für die identische Investition zu rechnen ist, kann auch ein Vorziehen der Investition vorteilhaft sein. In diesem Fall geht zukünftige Flexibilität verloren, da die Investition durch ihre technische Komplexität als irreversibel betrachtet werden kann. Jedoch wird gleichzeitig das Risiko, welches aus der unsicheren zukünftigen Entwicklung resultiert, reduziert bzw. umgangen. Diese Entscheidungssituation wird über das Modell abgebildet und für mehrere Fallstudien und Zukunftsszenarien beispielhaft analysiert.

Wenngleich die Arbeit in erster Linie auf die Entwicklung einer geeigneten Berechnungsmethodik für den geschilderten Anwendungsfall abzielt, zeigen die Ergebnisse der Fallstudien für eine Anlage in der EU und für eine indische Anlage, dass disruptive Gesamtkonstellationen erforderlich sind, um eine Beeinflussung der Entscheidung zu bewirken, im gegebenen Fall also ein Vorziehen der Investition. Dabei führen politische Instrumente wie Emissionsabgaben, welche für Unternehmen ausgabensteigernd wirken, eher zu einer Beeinflussung als einmalige, investitionsbezogene Förderprogramme. Ein allein durch Marktentwicklungen bedingter Anstieg der Investitionsausgaben in zukünftigen Perioden führt innerhalb einer als realistisch anzusehenden Entwicklung nicht zu einer vorgezogenen Investition.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ABS	Ammonium Bisulphates
BAT	Best Available Techniques
BAT-AEL	Best Available Techniques Associated Emission Levels
BBF	Biased Burner Firing
BOOS	Burner Out Of Service
BREF	Best Available Techniques Reference Document
C&C	Command and Control
CAPEX	Capital Expenditures
CAPM	Capital Asset Pricing Model
CEPCI	Chemical Engineering Plant Cost Index
CLRTAP	Convention on Long-range Transboundary Air Pollution
COP	Conference of the Parties
EEA	European Environment Agency
EEC	European Economic Community
EECCA	Eastern Europe, Caucasus and Central Asia
ELV	Emission Limit Value
EGTEI	Expert Group on Techno-Economic Issues
ESP	Electrostatic Precipitator
EU	European Union
FBC	Fluidized Bed Combustion
FCI	Fixed Capital Investment
FGD	Flue-gas Desulfurization
GBM	Geometric Brownian Motion
HHV	Higher Heating Value
ICAC	Institute of Clean Air Companies
IEA	International Energy Agency
IECM	Integrated Environmental Control Model
IED	Industrial Emissions Directive

IFC	International Finance Corporation
IPPC	Integrated Pollution Prevention and Control
LCA	Life Cycle Analysis
LCP	Large Combustion Plant
LCPD	Large Combustion Plant Directive
LED	Light Emitting Diode
LHV	Lower Heating Value
LNB	Low-NO_X-Burner
LSM	Least Squares Monte-Carlo-Simulation
NPV	Net Present Value
OECD	Organization for Economic Co-operation and Development
OFA	Over Fire Air
OPEX	Operational Expenditures
PC	Pulverized Coal
PDE	Partial Differential Equation
PM	Particulate Matter
PRTR	Pollutant Release and Transfer Register
R&D	Research and Development
ROA	Real Option Analysis
ROV	Real Option Value
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SWOT	Strengths Weaknesses Opportunities Threats Analysis
TCI	Total Capital Investment
TFTEI	Task Force on Techo-Economic Issues
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
US EPA	United States of America Environmental Protection Agency
VOC	Volatile Organic Compound(s)
WACC	Weighted Average Cost of Capital
WC	Working Capital
WHO	World Health Organization

List of Symbols and Indices

Chemical Symbols

Al_2O_3	Alumina
C	Carbon
Ca	Calcium
CO	Carbon monoxide
CO_2	Carbon dioxide
CH_4N_2O	Urea
H_2, H	Hydrogen
HCN	Hydrogen cyanide
H_2O	Water
K	Potassium
N_2, N	Nitrogen
Na	Sodum
NH_3	Ammonia
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
NO_3	Nitrogen trioxide
NO_X	Nitrogen oxides (collective term)
N_2O	Nitrous oxide
N_2O_3	Dinitrogen trioxide
N_2O_4	Dinitrogen tetroxide
N_2O_5	Dinitrogen pentoxide
N_2O_6	Dinitrogen hexaoxide
O_2, O	Oxygen
S	Sulfur
SiO_2	Silica

SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
SO_X	Sulfur oxides (collective term)
TiO_2	Titanium dioxide
V_2O_5	Vanadium (V) oxide
WO_3	Tungsten trioxide
PM*	Particular matter (dust)
VOC*	Volatile organic compound(s)

* PM and VOC are no chemical elements, but these abbreviations summarize several chemical elements and bonds with similar properties. Due to their particular relevance in the context of this work, they are mentioned here.

Mathematical Symbols

c	Price
C	Total cost
$\dot{C}$	Annual cost
CAP	Capacity
$CAPF$	Capacity factor
$CEPCI$	CEPCI factor
CF	Cash flow
CIF	Cash in flow
COF	Cash out flow
con	Concentration
CRF	Capital recovery factor
d	Factor for path 'down'
$\mathbb{E}$	Expected value
EF	Emission fees
f	Factor
FOM	Factor for operation and management expenses
HHV	Higher heating value

I	Investment
IT	Investment threshold
K	Strike price
L	Lifetime
LHV	Lower heating value
m	Mass
$\dot{m}$	Mass flow
$\Delta\dot{m}_{NOx}$	Abated NO_X emissions
M	Molar mass
MC	Number of Monte-Carlo paths
n	Power factor
N	Number
NCF	Net cash flow
NO_X	Factor for correction of NO_X load
NPV	Net present value
OP	Option price
Δp	Pressure drop
P	Power
PV	Project value
q	Probability
r	Interest rate
R	Return
ROV	Real option value
S	Stock price
$\bar{S}$	Long-run stock price average
Sul	Factor for correction of the sulfur content
$Slip$	Factor for correction of ammonia slip
SRF	Stoichiometric ratio factor
t	Time
T	Lifetime/decision making time
u	Factor for path ‘up’
v	Specific volume
V	Volume

$\dot{V}$	Volume flow/flow rate
W	Work
$\dot{W}$	Work per period (e.g. annual)
ΔW	Wiener process
WF	Work factor
x	Mass fraction
α	Biomass co-firing rate
β	Mean-reversion parameter
ε	Normally distributed random number
ϑ	Factor for correction of inlet temperature
η	Efficiency (production efficiency, abatement efficiency)
λ	Air/fuel ratio
μ	Drift rate
ρ	Concentration/density
σ	Volatility

Symbol Indices

The following table lists the indices that are used as subscripts in the equations of this work. Some short words are directly used (without abbreviation) in order to facilitate the reading and understanding of equations. These words are not listed in the following and are used as superscripts in the equations.

0	Zero/initial state
1°	Primary measures
a	Annual
act	Actual
adj	Adjusted
ash	Mineral residues of combustion (ash)
C	Carbon
cap	Capital
Cat	Catalyst

cia	Carbon in ash
CO_2	Carbon dioxide
dil	Diluted
dir	Direct
EF	Emission fees
el	Electric/electricity
eq	Equivalent
fix	Fixed
fg	Flue gas
fl	Full load
h	Hourly
H	Hydrogen
H_2O	Water
inv	Investment
j	Load level
k	Counting variable for sum functions
l	Losses perspective
mc	Monte-Carlo path
moist	Moisture
NEF	No emission fees
NOx	Nitrogen oxides
O, O_2	Oxygen
op	Operating
pd	Pressure drop
reag	Reagent
ref	Reference
reg	Regeneration (of catalyst)
s	Savings perspective
S	Sulfur
SCR	Selective catalytic reduction
SNCR	Selective non-catalytic reduction
spec	Specific
stoi	Stoichiometric

t	Time
t_0	Initial/current time
t^*	Next best time
th	Thermal
tot	Total
var	Variable
wat	Water
λ	At excess air ratio (not stoichiometric)

1 Introduction

In times of intensive debates on global warming and climate change, the issue of air pollution seemed to lose importance in public discussions, even though air pollution is proven to have a significant impact on human health and the environment (Gurjar et al. 2010). Policy continuously aimed at improving air quality by setting and tightening air quality standards and adapting the corresponding regulation over the last decades. Such regulation often enforces investments by the polluters in order to abate emissions that are caused by e.g. the production of goods, the provision of energy or transport.

Currently, the so-called diesel-gate affaire reveals difficulties of dealing with such a need for investments on a personal and institutional level and brings the issue of air pollution with nitrogen oxides (NO_X) in focus again. On an industrial level, investments are usually triggered by regulatory requirements that need to be fulfilled in order to get a permit for operating a plant. Nevertheless, there are several options for plant operators to react to such policy and political entities can incentivize certain courses of action in various ways. Possible investment strategies and policy instruments will be assessed in this work via a real option based appraisal model for economically non-beneficial environmental investments. NO_X emission control measures in large combustion plants will serve as exemplary application in this context. The delimitations, definitions, and characteristics of this task will be introduced in more detail in the following, with regard to the current situation and problem setting in order to derive the scope and the aims of the work at hand. [1]

[1] Parts of this research contribution have previously been published in Mayer et al. (2015), Mayer et al. (2016), Mayer et al. (2017), Mayer and Schultmann (2017), Schiel et al. (2019) and TFTEI (2015a). Passages of these publications were developed exclusively by the author of this work and are therefore used without citation.

1.1 Current Situation and Problem Setting

Figure 1-1 provides a brief overview of the considered setting with the three main pillars ‘industrial production’, ‘policy’ and ‘management’. They all influence the overall problem setting and will hence be introduced briefly in this introduction and in more detail in the following chapters.

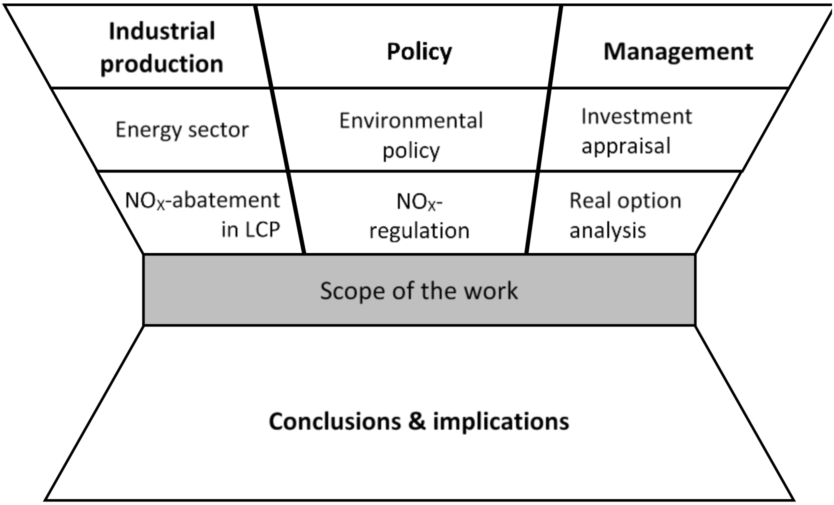

Figure 1-1: General framework with the three main influencing pillars for the task of this research [LCP: Large Combustion Plants].

In order to set the scope for the techno-economic assessment, a delimitation of the considered plants is necessary. This work considers fossil fueled large combustion plants (LCP), which are defined in the EU LCP Directive (EU 2001) as plants with a rated thermal input of 50 MW or greater.

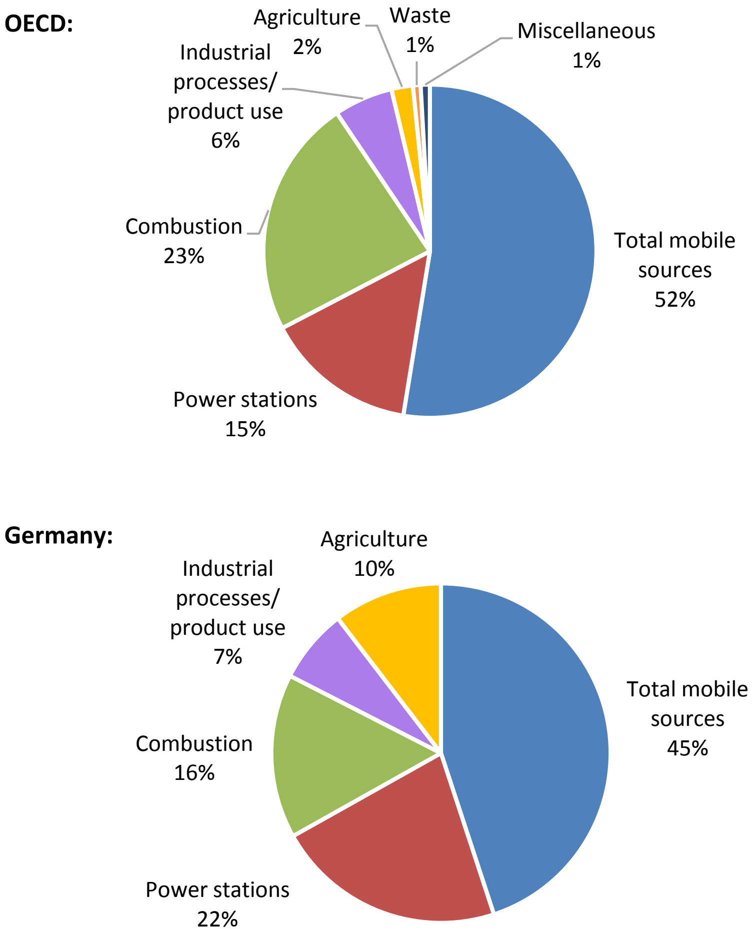

Figure 1-2: NO_X emissions in 2016 by sectors in the OECD region (except Israel, South Korea, and Mexico) and in Germany (OECD 2018a).

According to Figure 1-2 combustion units (still) contribute to a significant amount of the total NO_X emissions in the OECD region and in Germany.[2] While the combustion sector in the figure includes not only large combustion plants but also residential heating and small and medium-size combustion plants, a majority of the emissions from the power stations stems from LCP and further LCP are operated in the industrial processes sector.

For LCP, there are two technical strategies to abate NO_X emissions. The so-called primary measures aim at reducing the formation of NO_X during combustion, while the secondary measures are downstream flue gas cleaning installations that reduce the amount of NO_X present in the flue gas by chemical reduction. The costs of primary measures are generally lower than those of secondary measures, yet their abatement potential is limited. For an LCP, the costs of NO_X control are significant and can exceed 20 % of the total costs for environmental controls (Lani et al. 2008).

Important contributions to the techno-economic assessment of NO_X abatement installations in large combustion plants in this research stem from works of TFTEI, the Task Force on Techno-economic issues, formerly known as EGTEI (Expert Group on Techno-economic Issues) (TFTEI 2015b; UNECE 2015b).[3] Since 2002, TFTEI is working under the UNECE (United Nations Economic Commission for Europe) in the framework of the CLRTAP (Convention on Long-range Transboundary Air Pollution). The group is a collaboration of administrative, scientific and industry experts that work together in order to develop information about techno-economic aspects of emission abatement. This information shall be of use for the whole UNECE region, with a particular focus on the EECCA countries (Eastern Europe, Caucasus, and Central Asia).

2 OECD: Organization for Economic Co-operation and Development. In the figure, the OECD region excludes Israel, South Korea and Mexico due to lacking data.

3 The author of this work directly contributed to the works of TFTEI since 2014 as a member of the Technical Secretariat and was directly responsible for the tasks considered in this work, i.e. the techno-economic assessment of NO_X abatement in LCP.

The history of transnational NO_X abatement policy in the UNECE region started in the late 1980ies with the adoption of the Sofia Protocol (UNECE 1988) and since then, the emission limits for NO_X emissions from LCP but also from other installations and sectors have been tightened in several steps. The implemented abatement technologies developed accordingly. After a first phase of installation of primary control measures that led to major reductions of total NO_X emissions, more and more secondary measures had to be installed in order to meet tightening regulation (Brandwood 9/27/2018). The latest amendment of regulation for LCP was the Best Available Techniques Reference Document (BREF-LCP) that was published in 2017 (Lecomte et al. 2017). It needs to be transferred in national regulation by the EU member states within one year and the amended emission limits will be in force from 2021 on.

This BREF document affects a considerable number of plants. In Germany, about half the capacity of coal-fired plants may need to revise or upgrade their abatement measures (Ruhrberg 2016). This order of magnitude is confirmed for the whole EU region by Scarbrough et al. (2017). Therefore, there is a clear need for NO_X abatement investments in the EU. In countries outside the EU region that just started implementing NO_X regulation, the investment potential is even larger.

Nevertheless, the costs for NO_X control measures that result from the new regulation can still be considered low in comparison to e.g. the CO_2 allowance cost induced by the European Trading System ETS (Hodgson 9/26/2018). Therefore, it is considered unlikely that NO_X abatement regulation leads to closure of plants or to a significant adaptation of operation, such as a reduction of the annual operating time. Hence, the system boundary for the assessments in this work is drawn around the emission abatement installation. All cash flows that are caused by the installation are investigated, whereas the operation and the resulting cash flows of the plant itself are considered constant and are thus left aside.

Regarding the managerial perspective, traditional investment appraisal focuses on the evaluation of investment alternatives rather than assessing the optimal timing of investments. Typical methods for 'traditional' investment appraisal are static methods such as cost or profit comparisons, the average rate of return or the payback period method, or dynamic methods such as the net present value approach. A more recent development that aims at better understanding actual investment decisions in the framework of new institutional economics and targets e.g. the problem of investment timing directly is the real option analysis (ROA). Based on option valuation theory of the financial sector, ROA aims at quantifying the monetary value of managerial flexibility and is of particular interest for the application at hand.

1.2 Aim and Approach

The appraisal methods for investment decisions usually focus on investments that gain profits for the investor. Mandatory investments, in particular if they do not gain revenues, are not targeted by such approaches, as they have to be executed anyways. For plant operators and policy-makers, however, it is crucial to assess the economic impact of environmental regulation. Plant operators aim at identifying optimal strategies to deal with such regulation. In the case of mandatory investments, one of the most relevant matters (if the technical alternatives are limited) is the timing of investments. For policy-makers, it is particularly relevant to assess possible economic impacts of regulation in order to avoid e.g. leakage effects, i.e. the relocation of production facilities and hence of emissions to other countries. Furthermore, a detailed understanding of industrial decision-making is necessary in order to develop strategies and instruments for influencing it.

A detailed overview of existing literature will be prepared in the following chapters. In order to derive the main research questions, a first summary is provided here. There is a vast number of publications with regard to all three decision-influencing pillars. Regarding the techno-economic aspects of NO_X

abatement, the most important references with regard to the work at hand are Strauss (2016), TFTEI (2015a) and US EPA (2016).

Regarding NO_X regulation from a political perspective, there is a broad number of countries having such regulation in force. Several of these countries also provided further scientific reports with regard to the impacts of and experiences with different policy measures.

The managerial aspect of investment decision-making can be considered the least well investigated. Even though there is a broad variety of publications that apply real options theory to environmental investments, all these studies focus on profitable investments, i.e. they calculate the thresholds for e.g. emission fees in order to trigger environmental investments from an economic perspective. The aspect of non-profitable investments has, to the best of the author's knowledge, not been investigated so far.[4] Exemplary publications that assess profitable environmental investments are by Abadie and Chamorro (2008) and Insley (2003) and many more will be mentioned in the following chapters.

Furthermore, the influence of political ambiguity has also been investigated, for example by Julio and Yook (2012) and Welling et al. (2015). Both mention a considerable impact of policy on industrial investment decision-making that is not only caused by direct policy measures but also by ambiguity with regard to the future development of policy.

The resulting three main research questions for the work at hand are summarized in Table 1-1. After two introductory chapters with the fundamental knowledge for the development of the models, the chapters 4 and 5 introduce the modeling approach and chapter 6 investigates exemplary case studies and the resulting implications with regard to policy-making.

[4] The investments may be profitable for society, if external costs are considered. From a company internal perspective they are not profitable, as they do not gain revenues.

Table 1-1: Summary of the main research questions [CAPEX: Capital Expenditures; OPEX: Operational Expenditures].

Research question	Related chapter
How can the CAPEX and OPEX for NO_X abatement installations in LCP be estimated precisely and efficiently in the early stages of investment planning or by company external entities?	4
How can the optimal timing of the investment be assessed based on the ROA approach?	5
Which policy instruments influence investment decisions in the considered framework in which way?	6

Figure 1-3 displays the structure of the modeling approach to be developed. It starts with a broad variety of input data, which is a crucial factor due to the technical complexity of the investigated installations. Based on this data, a techno-economic model is developed, which aims at quantifying the CAPEX (Capital Expenditures) and OPEX (Operational Expenditures) for a NO_X abatement installation in a specific plant (cf. chapter 4). The object of this assessment is a single plant with all its specifics and characteristics. The model targets study level accuracy (+/- 25 %) as it is not able to and does not aim at replacing a detailed on-site bid proposal by manufactures. A macroeconomic or cross-sectoral study is not in the scope of this work, as the technical specifics of individual plants shall be investigated in detail. Nevertheless, it is possible to identify reference installations and to derive general conclusions thereof, in particular with regard to the impacts of policy measures.

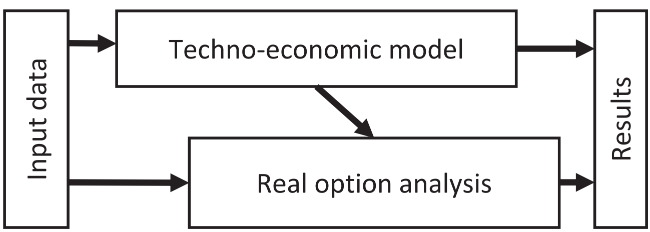

Figure 1-3: Schematic overview of the modeling approach.

The second part of the modeling approach is the real options model, which investigates investment decision-making with a particular focus on the optimal timing of mandatory investments that have to be executed within a certain timeframe, the so-called adaptation time. A common strategy for non-profitable investments is the delay of the investment as far as legally feasible. In case of disruptive settings, such as significantly increasing investment expenditures or the implementation of policy measure s such as emission fees, it may be advantageous for the investor to advance the investment. Such an advancement may also be of interest for the public and hence for policy, as it leads to a faster reduction of air pollution. Both the results of the techno-economic model and additional data serve as input values for this model, which is introduced in detail in chapter 5. It is a numerical model that focuses on applicability and transparency rather than on achieving perfect analytic results. This does not mean that the results are wrong, but certain simplifications are considered acceptable in order to increase transparency while the impact on the results is considered acceptable within the aim of study-level accuracy.

Finally, several case studies and scenarios will be investigated in chapter 6 in order to explain the calculations in detail and assess the results aiming at deriving policy conclusions with regard to possible impacts of policy measures. This work clearly focusses on the methodological aspect, i.e. the development of a calculation model for mandatory environmental investments that do not gain profits. Therefore, the results provide an order of magnitude with regard to the investments and costs of NO_X abatement installations and impacts of policy measures but do not aim at quantifying the monetary outcomes of certain policy measures in exemplary countries. This would be possible if a broad set of data with regard to all plants in a country was available, but goes beyond the scope of this work as such detailed data is not publicly available.

2 Nitrogen Oxide Emissions from Large Combustion Plants

Large combustion plants (LCP) are not the only, but an important emitter of NO_X worldwide. Even though the total share of NO_X emissions in the EU declined over the last centuries (cf. Figure 2-1), there is still need and potential for improvement. This has been implicitly confirmed in 2017 by the revised BREF-LCP that lowers the limits for NO_X emissions of LCP again (Lecomte et al. 2017). Large combustion plants are in the following defined as primarily fossil fuel burning plants with a capacity of 50 MW or more. Not all, but a majority of LCP belong to the energy sector (Lecomte et al. 2017). Therefore, this sector is in the focus of this chapter and the whole work.

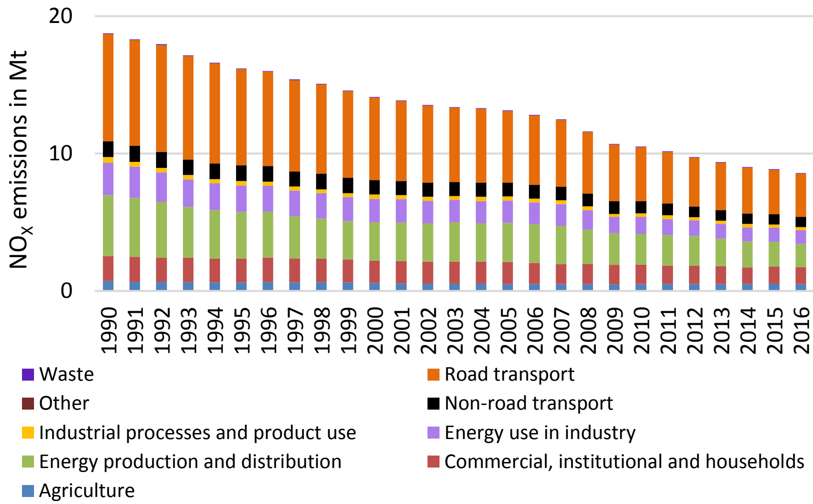

Figure 2-1: NO_X emissions of the EEA-33 countries per sector between 1990 and 2016 (European Environment Agency 2018a).

NO_X emissions from LCP can be reduced by primary or secondary emission reduction techniques. Primary techniques influence the combustion process directly in order to avoid or reduce the formation of NO_X. Secondary measures are techniques that clean the flue gas by reducing existing NO_X particles to nitrogen (N_2) and oxygen (O_2).

In the following, the basic characteristics of NO_X including their formation will be investigated and an overview of available abatement techniques will be provided. Furthermore, the political landscape including existing types of policy instruments and an overview of the legislation worldwide with regard to NO_X emissions of the energy sector will be provided.[1]

2.1 Characteristics and Formation of NOx

Atmospheric nitrogen is usually present as N_2 with a strong triple bond. It is chemically inert and needs energy to break into elementary nitrogen, which then reacts with oxygen to form nitrogen oxides (Kolar 1990). The group of nitrogen oxides is displayed in Table 2-1. The most relevant compounds in the following are NO and NO_2 as they are primarily formed during combustion (Kolar 1990). NO_2, which is predominantly formed of NO in ambient air is a red-brown or purple gas with a characteristic ozone-like smell (Kolar 1990).

The following section introduces the environmental impacts of NO_X emissions and explains the formation mechanisms, which are relevant for the understanding of the functional principles of emission abatement technologies. Furthermore, the impacts of plant design and operation, including the increasing flexibility demand caused by fluctuating feed-in of renewable energy will be assessed.

[1] Parts of this chapter have previously been published in Mayer et al. (2015), Mayer et al. (2016), Mayer et al. (2017) and TFTEI (2015a).

Table 2-1: Oxides of nitrogen (Kolar 1990).

Chemical notation	Name	Oxidation number
N_2O	Nitrous oxide (laughing gas)	+1
NO	Nitrogen monoxide	+2
N_2O_3	Dinitrogen trioxide	+3
NO_2	Nitrogen dioxide	+4
N_2O_4	Dinitrogen tetroxide	+4
N_2O_5	Dinitrogen pentoxide	+5
NO_3	Nitrogen trioxide	+6
N_2O_6	Dinitrogen hexaoxide	+6

2.1.1 Environmental and Health Effects of NOx Emissions

US EPA (1998) summarizes the most important impact categories and mechanisms of NO_X concerning humans and the environment as listed below. The information is confirmed and further detailed by Kolar (1990), Reis (2010), UNECE (2015a) and Wellburn (1997). Most important references regarding this subject are about 20 to 30 years old when research aimed at understanding the impacts of air pollution in detail. Even though the references are rather old, they are still valid and cited in more recent literature.

Ground-level Ozone (Smog): NO_X and volatile organic compounds (VOC) react in the presence of heat and sunlight. The resulting ozone may damage lung tissue and reduce lung function. Ozone can also damage vegetation and reduce crop yields (Kolar 1990; US EPA 1998).

Acid Rain: NO_X and sulfur dioxide (SO_2) react with other substances in the air to form acids, which fall to earth as acid rain (as well as acid fog, snow, or dry particles). Acid rain causes lakes and streams to become acidic and unsuitable for many fish. It further damages forests and causes deterioration of cars, buildings and historical monuments (Singh and Agrawal 2008; US EPA 1998).

Water Quality Deterioration: Increased nitrogen loading in water bodies upsets the chemical balance of nutrients used by aquatic plants and animals. Additional nitrogen accelerates eutrophication, which leads to oxygen depletion and reduces fish and shellfish populations (Helsinki Commission 2005; US EPA 1998).

Toxic Chemicals: NO_X reacts with common organic chemicals in the air to form a wide variety of toxic products, some of which may cause biological mutations. Examples are the nitrate radical, nitroarenes, and nitrosamines (US EPA 1998).

Global Warming: Nitrous oxide is a greenhouse gas. It accumulates in the atmosphere with other greenhouse gases and contributes to climate warming (Lammel and Graßl 1995; US EPA 1998).

Particles: NO_X can react with ammonia, moisture, and other compounds to form nitric acid vapor and related particles. These particles affect the respiratory system, may damage lung tissue and cause premature death. Small particles penetrate deeply into sensitive parts of the lungs and can cause or worsen respiratory and/or heart diseases (Gurjar et al. 2010; US EPA 1998).

Visibility Impairment: Nitrate particles and nitrogen dioxide can block the transmission of light and may reduce visibility in urban and other polluted areas (Kolar 1990; US EPA 1998).

2.1.2 Formation Mechanisms

Nitrogen oxide formation during combustion processes is caused by two sources of nitrogen. The nitrogen bound in the fuel and the nitrogen in the combustion air can be oxidized according to the reaction paths presented in the following. Detailed information regarding the reactions, reaction kinetics, and influencing factors are provided in industrial combustion literature, such as Joos (2007), Kolar (1990), Möller (2003), Schnelle et al. (2016) and Warnatz et al. (2006).

The mechanisms described in the subsections below explain the formation of NO, which is directly formed in combustion processes and thus defined as a primary pollutant. A part of this NO further reacts to NO_2 according to eq. (2-1), forming the secondary pollutant NO_2 (Möller 2003).

$$2\mathrm{NO} + \mathrm{O}_2 \longrightarrow 2\mathrm{NO}_2 \tag{2-1}$$

This reaction starts directly after the formation of NO in the boiler. Therefore, a rate of 5 to 10 % of NO_X emissions of a power plant is NO_2 (Möller 2003). Outside the plant, the reaction continues until the majority of NO is oxidized to NO_2 (Möller 2003). Therefore, the total nitrogen oxide emissions are usually summarized as NO_X, while the emission value for industrial sources is per definition calculated as NO_2 in most regions/regulations (Möller 2003; UNECE 2013). The conversion rate between the mass-based emission values of NO and NO_2 is 1.53, which accounts for the relation between the molecular weights of NO_2 and NO.

2.1.2.1 Thermal NO_X (Zeldovich Mechanism)

The thermal NO_X mechanism requires, as the name implies, comparably high temperatures and is further enforced by high oxygen contents (Joos 2007). According to Möller (2003) temperatures above 1000 K are required to achieve the necessary activation energy for the reaction. Equations (2-2) to (2-4) display the three basic reactions of thermal NO_X formation. It was first published in Zeldovich (1946) and is thus also named Zeldovich mechanism (Joos 2007; Möller 2003; Warnatz et al. 2006). As molecular nitrogen and oxygen (N_2, O_2) do not react directly, the presence of radicals is necessary for these reactions (Kolar 1990). The actual reactions in the combustion chamber are more complex and include several more subreactions. More details are provided in e.g. Kolar (1990). Yet, for the general understanding of this formation mechanism and how the NO_X formation can be influenced by technical measures, these basic reactions are sufficiently detailed.

$$O + N_2 \longrightarrow NO + N \quad (2\text{-}2)$$

$$N + O_2 \longrightarrow NO + O \quad (2\text{-}3)$$

$$N + OH \longrightarrow NO + H \quad (2\text{-}4)$$

Based on the chemical characteristics of the reaction, there are three alternatives to reduce the NO_X formation according to this mechanism:

- Reducing the number of nitrogen molecules (N_2)
- Reducing temperature
- Reducing the availability of oxygen radicals (O) (Joos 2007).

According to Joos (2007) and Warnatz et al. (2006), the estimation or simulation of available oxygen radicals is difficult and often defective, as the local situation in the flame front may differ from the equilibrium.[2] This makes a mass-balancing and thus a reasonable estimation of NO_X emissions without detailed knowledge of the local combustion conditions practically impossible (Joos 2007).

2.1.2.2 Prompt NO_X (Fenimore Mechanism)

An alternative reaction path is based on the reaction products of CH-radicals, which occur plenty in high fuel concentrations with few oxygen radicals. The CH-radicals react with the nitrogen in the ambient air forming HCN (hydrogen cyanide) which then reacts in several steps to NO (cf. eq. (2-5)) (Joos 2007).

$$CH + N_2 \longrightarrow HCN + N \ldots \begin{matrix} \nearrow NO \\ \searrow N_2 \end{matrix} \quad (2\text{-}5)$$

This reaction, first described by Fenimore (1979), is characterized by its fast devolution, which means that the residence time is hardly relevant and thus

[2] Joos (2007) mentions up to factor 10 higher concentrations of O radicals in the flame front compared to the equilibrium concentration.

explains the designation ‘prompt NO’ (Joos 2007). Because of the formation being based on the existence of a radical (CH), it is in this case even more difficult to calculate the resulting amount of NO than it is for thermal NO (Warnatz et al. 2006).

2.1.2.3 Conversion of Fuel-bound Nitrogen

The third important mechanism of NO_X formation converts the nitrogen content of the fuel. Heavy fuel oils and coals contain about 1 % of nitrogenous compounds (Joos 2007; Warnatz et al. 2006). Under approximately stoichiometric combustion conditions, this nitrogen is almost completely oxidized to NO, via several intermediates and oxidation steps (Joos 2007).[3] In an air-rich environment, the oxidation rate is lower, about one-third of the nitrogen reacts to N_2. In case of an air-lean environment, the direct formation of NO is reduced as well, however, the formation of other compounds such as HCN or NH_3 (ammonia) that react to NO in the atmosphere is enforced (Joos 2007).

2.1.2.4 Nitrous Oxide (N_2O) Mechanism

The three mechanisms described above are the most relevant for industrial combustion facilities. Another mechanism analogous to the thermal NO_X mechanism is based on the formation of nitrous oxide (N_2O). It was first postulated by Wolfrum (1972), more details are provided by e.g. Warnatz et al. (2006). In contrast to the thermal NO_X mechanism, it requires a comparably high pressure and is thus more relevant for gas turbines or other high-pressure applications that are not in the scope of this work (Joos 2007).

2.1.2.5 Total NOx formation

Figure 2-2 displays the interaction between the three most relevant NO formation mechanisms, depending on the temperature. Increasing temperature leads to significant increases of NO formation, which indicates a first

[3] A more detailed description is provided in Möller (2003).

important strategy for primary NO_X abatement, the reduction of (peak) combustion temperatures. Further reduction strategies will be discussed in more detail in 2.2.1.

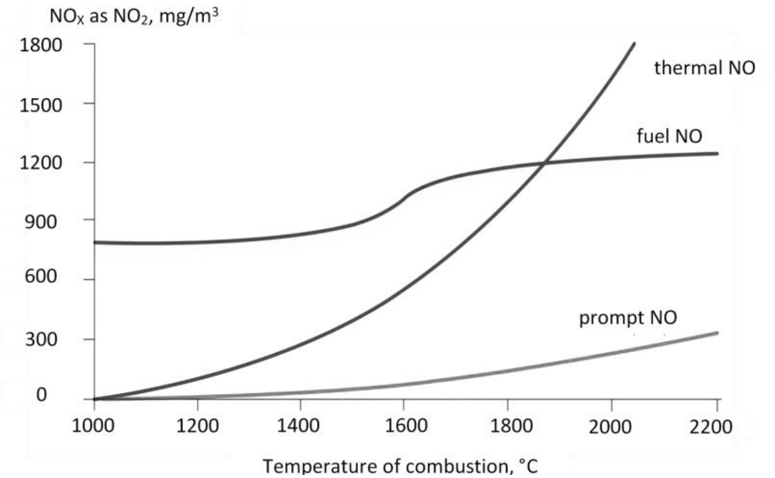

Figure 2-2: NO_X formation caused by the three predominant formation mechanisms depending on the temperature (OECD (1993) quoted in Wiatros-Motyka and Nalbandian-Sugden (2018)).

2.1.3 Effects of Plant Design and Operation Strategy

As discussed above, NO_X formation in combustion processes depends on several complex mechanisms. Therefore, it can be significantly influenced by control and regulation of the combustion process itself. Furthermore, modified operating schemes with regard to increasing production flexibility need to be investigated regarding their influence on the NO_X formation processes. Startup and shutdown cycles become shorter and more frequent and part load operation is required to regulate demand fluctuations. The effects of these modified operating conditions with regard to NO_X formation will be analyzed in the following.

2.1.3.1 Plant Design and Operation

The plant design and particularly the burner and boiler design influence the NO_X formation significantly. Wiatros-Motyka and Nalbandian-Sugden (2018, 16-18) mention several relevant design aspects with regard to coal-fired combustion plants. They state that e.g. wet bottom boilers operate at higher temperatures that lead to higher NO_X formation levels. Tangential firing systems generally produce less NO_X than cyclone, U- or wall-fired burners, assuming the same coal input, as the nitrogen content of the coal also influences the formation processes (particularly fuel NO). More details regarding NO_X formation in natural gas combustion are provided in Löffler et al. (2006). A broad overview of plant configurations and resulting NO_X levels is impossible due to the manifold types of configurations, burners, and coals in use. Therefore, a careful selection of an appropriate reference plant is recommended if NO_X levels of new plants shall be derived of comparisons with existing plants.

Regarding operation, two major aspects influence the NO_X emissions of a plant. First, the combustion operation and control influences the formation of NO_X as described above and in 2.2.1. Furthermore, the operation and control of secondary NO_X abatement installations are of relevance, as the chemical processes of NO_X abatement also require a precise control of several physical parameters such as temperature, residence time, etc. More details will be provided in 2.2.2 and 2.2.3.

2.1.3.2 Part Load Operation

According to the formation mechanisms of NO_X, lower emission levels can be expected in case of lower load operation due to reduced combustion temperatures. Older references such as Baumüller et al. (1987) and Blakeslee and Burbach (1973) confirm this theory. Newer references, however, show approximately constant emissions across different load levels. Examples are provided in Brandwood (9/27/2018), Coombs et al. (2004), Kather et al. (1997) and Kather et al. (2013).

A possible explanation is the dissemination of primary NO_X reduction measures and a more and more advanced combustion control. Baumüller et al. (1987), as well as Coombs et al. (2004), show that primary NO_X abatement systems operate more efficiently under design conditions (i.e. at full load) than in part load operation. Furthermore, secondary abatement techniques can be controlled rather precisely in order to achieve a certain emission level independently of the load level.

Consequently, if no detailed data is available, it is considered reasonable to assume that the lower formation rate at lower load levels is compensated by the lower efficiency of combustion and/or the down-regulation of secondary emission control systems, not only for solid but also for liquid and gaseous-fueled plants.

Furthermore, particularly coal-fired plants are restricted regarding the minimum load level for continuous operation. According to Schroeder (2017), a typical limitation for conventional coal-fired plants[4] is a minimum load level of about 40 % full load. This minimum is caused by the comparably high necessary temperatures for safe combustion. Below this level, liquid or gaseous fuels have to be burnt additionally in order to support the combustion. In practice, this is avoided in continuous operation and used for startup and shutdown only. Liquid and gaseous fueled plants are more flexible, yet their flexibility may be limited as well, for example by the required temperature level for emission control measures (Schroeder 2017).

[4] Conventional plants are here defined as plants that are not specifically designed and controlled for low load operation as described in Schroeder (2017).

2.1.3.3 Startup and Shutdown Cycles

Startup and shutdown processes differ a lot, depending on the combustion system, fuel, size of the plant, type of start[5], etc. Tomei (2015) mentions a typical startup time for large coal-fired plants of 4 to 6 hours, with deviations in both directions. Regarding the startup of NO_X abatement, Kokopeli et al. (2013) describe even longer times, especially for SCR[6] systems. Furthermore, the number of startups per year differs a lot among different plants. An average number for large coal-fired plants in the USA in 2011 and 2012 was 10 starts per year. Some plants, however, conducted up to 100 starts per year (Kokopeli et al. 2013).

Figure 2-3 displays one startup, operation and shutdown cycle and the corresponding stack emissions of an exemplary coal-fired plant according to Kather et al. (2013). It shows a massive increase in NO_X emissions (up to 900 mg/Nm³) during startup, while the emissions during continuous operation fluctuate around 100 mg/Nm³. The shutdown also displays increasing NO_X emissions, yet at a far lower level than during startup. The $DeNO_X$ system (SCR) is automatically controlled during startup and operation depending on the temperature of the catalyst (Kather et al. 2013).

This example provides interesting insights regarding the exemplary installation, yet it is not sufficient to draw general quantitative conclusions thereof for a variety of plants. As mentioned already, further literature is scarce. Biofuelwatch (2014) provides an overview of publications regarding startup and shutdown emissions of power plants. Several of the listed publications focus on dioxin or other toxic emissions. Only two studies with a special emphasis on NO_X are mentioned: Bivens (2002) and Kokopeli et al. (2013).

---

5 Plant operators differ between hot, warm, and cold starts, depending on the time between shutdown and new start. Kokopeli et al. (2013) define for coal-fired plants: hot start: offline for 24 hours or less, warm start: offline for 25 - 119 hours, cold start: offline for > 120 hours.

6 SCR: Selective Catalytic Reduction. This secondary NO_X abatement technique will be introduced in detail in section 2.2.2.

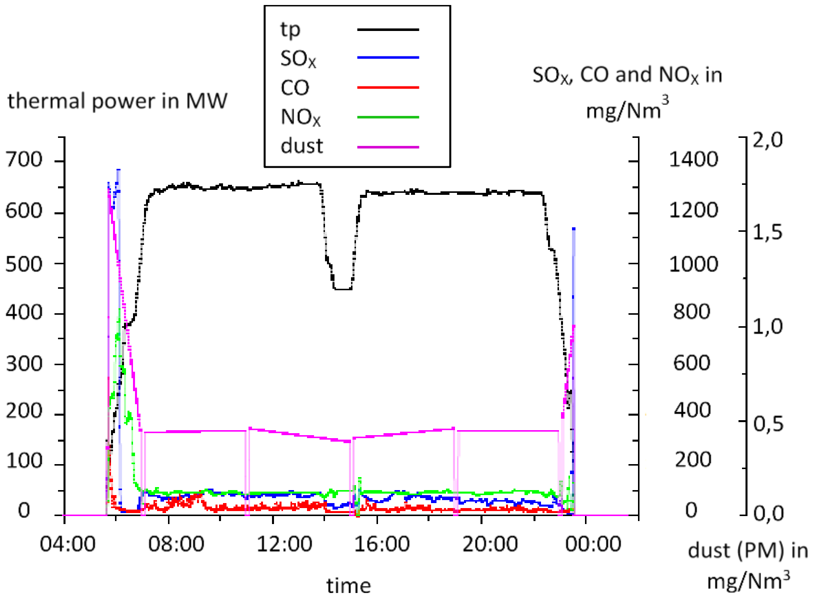

Figure 2-3: Thermal power and the related emissions over time during startup and shutdown of a coal-fired combined-cycle plant (Kather et al. 2013) [tp: thermal power].

Kokopeli et al. (2013) focus on the time between the beginning of operation and the stabilization of NO_X emission levels, yet without mentioning the total amount of emissions generated during this time. Bivens (2002) investigates gas turbine plants and is thus of limited use for this work. However, it confirms the difficulty to estimate, measure, control and regulate emissions during startup and shutdown. These difficulties are based on several reasons with most of them corresponding to the complex physical and chemical combustion and emission formation processes that are affected by an unmanageable number of influences. The author states that the derivation of startup emission estimations by multiplying the operating emissions by "*mythical emission factors (…) is a perfect example of making up numbers and should be considered unacceptable because it is fundamentally unsound*" (Bivens 2002, p. 13).

Even though this statement is made in the context of operation permitting, it emphasizes the difficulty to forecast startup and shutdown emission values. Nevertheless, the author confirms that the consideration of (measured) emission data for startups and shutdowns is important to evaluate the plant performance for longer periods. Therefore, average values may be assumed for the estimation of annual emission values that are expected to be more reliable than the forecasting of emissions for one single startup (Bivens 2002).

Consequently, analyzing the scheduled operation of a considered plant during the early stages of investment planning is recommended. If exceptionally many startup and shutdown cycles are envisaged, it may be reasonable, if not necessary, to analyze these processes in more detail and consider the correlating emissions.

2.2 NOx Control Techniques

Emission abatement installations in industrial combustion plants can be classified in two main categories: Primary measures avoid or reduce the formation of pollutants during combustion. Secondary measures reduce the amount of pollutants in the flue gas via flue gas treatment, before emitting it into the environment (end-of-pipe-technologies). While the general definition stands for various pollutants, the following chapters provide an overview of the relevant techniques for NO_X emission abatement. After a brief introduction on primary measures, the two most important secondary measures, Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR) will be presented. Finally, an outlook considering emerging techniques as well as an overview of abatement potentials will be provided. Further information about the technologies, their characteristics, fields of application and techno-economic evaluations are available in various scientific publications and reference documents of political or administrative entities.

Some examples are the documents of Beckmann (2011), Ebeling (1999), Lecomte et al. (2017), Falcone Miller and Miller (2010), Kolar (1990), Rentz (1979), Rentz et al. (1999) and US EPA (2016).

2.2.1 Primary Measures

Primary measures reduce the formation of pollutants; hence, they aim at establishing conditions that are unfavorable for the formation mechanisms described in chapter 2.1.2. Lani et al. (2008) mention the 'three T' of combustion: temperature, time and turbulence as critical influencing parameters. The flame temperature, the residence time at a certain temperature and the degree of fuel/air mixing influence the NO_X formation massively (Lani et al. 2008). Complemented by the influence of the nitrogen content of the fuel and the quantity of excess air, four promising NO_X abatement strategies, summarized in Table 2-2, can be derived (Joos 2007).

Table 2-2: Overview of measures aiming at reducing NO_X formation in large industrial combustion processes (adapted from Joos (2007) and Warnatz et al. (2006)).

Measure	Targeted mechanism	Technical abatement principal
Reducing peak temperatures	Thermal NO_X	Flue gas recirculation Staged combustion
Reducing oxygen content	Fuel NO_X	Flue gas recirculation Staged combustion
Reducing fuel-bound nitrogen	Fuel NO_X	Fuel switch
Reducing residence time in hot and O_2-rich environment	Thermal NO_X	Efficient dilution and ventilation Pre-combustion mixture (fuel + air)

The technical principles described above have been transferred in several primary NO_X emission control techniques as described in the following. One important technique is the staged combustion (air staging). It separates two combustion zones: a lean-air zone with lower temperature (due to incomplete combustion) and limited availability of oxygen (due to over-stoichiometric conditions) followed by a zone with excess air that enables complete combustion while ensuring short residence times and fast cooling due to efficient dilution and mixing (Joos 2007). This approach is also called OFA (over fire air) and is often used in combination with Low-NO_X-Burners (LNB) (Lani et al. 2008).

The flue gas recirculation lowers the maximum temperatures by dilution and cooling with inert combustion products. The pre-combustion mixture of fuel and air facilitates the desired combustion reactions and avoids local zones of insufficient mixing that may cause undesired reactions (Joos 2007; Kolar 1990).

The principle of fuel staging is similar to the air staging approach. The fuel is injected into the boiler at different positions. Thereby, different combustion zones are created as displayed in Figure 2-4. The primary combustion zone is located close to the bottom of the boiler. The majority of the fuel is injected and burned in this zone in a stoichiometric or over-stoichiometric environment. The NO_X formed in this environment is then reduced in the reburn or reduction zone. In this second zone, additional fuel (typically 10 to 25 % of the total fuel input) is injected and creates a fuel rich environment (Lani et al. 2008). High temperatures and a lack of oxygen in this zone, lead to a reduction of NO to N_2 in this zone. In the third zone (burnout zone) additional air is added in order to complete the combustion at lower temperatures (Lani et al. 2008; Zabetta et al. 2005).

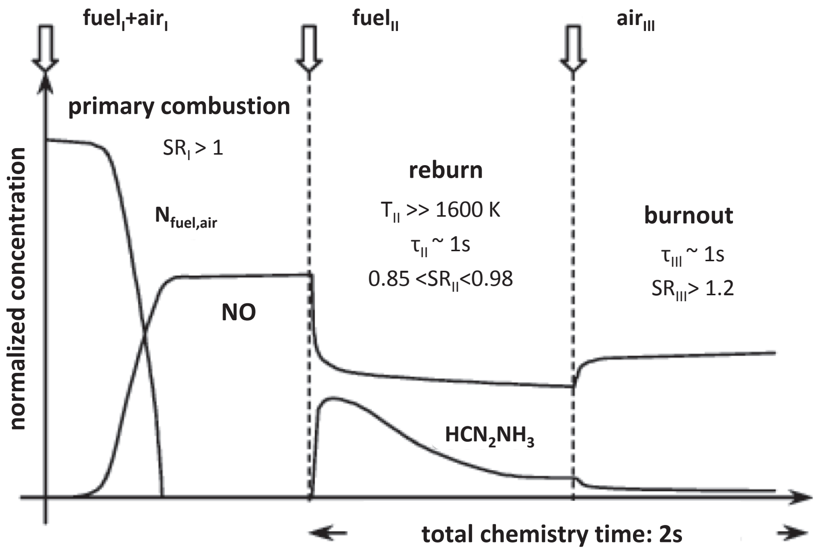

Figure 2-4: Combustion zones with fuel staging (Zabetta et al. 2005).

Low-NO_X Burners (LNB) control the mixing of fuel and air following the principles described in Table 2-2 and in particular those of staged combustion. Therefore, both flame temperature and oxygen concentration during particular phases of combustion are to be reduced, in order to reduce thermal NO_X and fuel NO_X production (Lani et al. 2008).

Apart from these basic techniques, there are several more approaches mentioned in literature, such as burners out of service (BOOS) or biased burner firing (BBF) (Kolar 1990). These approaches, however, are based on the same principles and mechanisms as those described above, they are just different technical implementations and will hence not be discussed in further detail in this work.

2.2.2 Selective Catalytic Reduction (SCR)

The selective catalytic reduction (SCR) is the best performing technique in terms of NO_X reduction rates and hence the most popular NO_X control technique on a global scale (Sloss 2017). At the same time, it is the most complex and cost-intensive technique. More details about its structure and functionality, necessary components and possible configurations will be presented in the following.

2.2.2.1 System, Components and Configuration

The principle of an SCR is to reduce NO_X by oxidation of ammonia. Therefore, a reagent is injected into the flue gas upstream of a catalyst unit, which is integrated into the flue gas processing. NO_X conversion takes place on the catalyst surface, usually at temperatures between 300°C and 450°C (Lecomte et al. 2017).[7] The catalyst allows reduction at a lower and broader temperature range than the thermal reduction without catalyst (cf. SNCR). Equations (2-6) to (2-8) display the chemical reactions between NO, NO_2, and ammonia (NH_3), which is commonly used as reagent (Schultes 1996; US EPA 2016).[8]

$$2\mathrm{NO} + 2\mathrm{NH_3} + \frac{1}{2}\mathrm{O_2} \xrightarrow{\text{catalyst}} 2\mathrm{N_2} + 3\mathrm{H_2O} \tag{2-6}$$

$$2\mathrm{NO_2} + 4\mathrm{NH_3} + \mathrm{O_2} \xrightarrow{\text{catalyst}} 3\mathrm{N_2} + 6\mathrm{H_2O} \tag{2-7}$$

$$6\mathrm{NO_2} + 8\mathrm{NH_3} \xrightarrow{\text{catalyst}} 7\mathrm{N_2} + 12\mathrm{H_2O} \tag{2-8}$$

An SCR system consists of several components. The two most basic units are the injection unit and the catalyst unit. Furthermore, various auxiliary components are needed, depending on the design of the installation. Examples

---

7 Depending on the type of catalyst/configuration used, wider temperature ranges of 170 °C to 510 °C may be possible (Lecomte et al. 2017).

8 The detailed reaction kinetics are very complex with more than 30 subreactions to be considered for modeling the abatement behavior of NO_X (Schultes 1996).

are reagent storage and transport systems, a flue-gas reheating unit, and additional fans to overcome the pressure drop of the flue gas caused by the catalyst unit (a more detailed overview is provided by US EPA 2016).

The need for and design of such additional components, as well as other operating parameters of an SCR, depend on the configuration of the flue gas processing system of the plant. Figure 2-5 illustrates the three most common configurations, the high-dust, low-dust, and tail-end system.

In the high-dust configuration, the SCR reactor is located upstream of the ESP and FGD[9] (or different particulate and SO_X removal installations). The catalyst is therefore exposed to fly ash and chemical compounds in the flue gas. Therefore, catalyst erosion and poisoning may occur (cf. section 2.2.2.3 and Wiesel et al. 2017). These issues can be addressed by proper design; nevertheless, this configuration is particularly suitable for installations with comparably clean fuels (Falcone Miller and Miller 2010).[10]

The low-dust configuration consists of the SCR reactor located downstream of the ESP but upstream of the FGD. Hence, the degradation of the catalyst by fly ash erosion is reduced, yet it requires a costly hot-side ESP or a flue gas reheating system to maintain the optimum operating temperature for the SCR (Falcone Miller and Miller 2010). In the tail-end configuration, the SCR reactor is installed downstream of both ESP and FGD unit. It is frequently used in retrofit installations with space limitations and it may reduce overall catalyst cost. However, this configuration is typically more expensive than the high-dust configuration due to flue gas reheating requirements (Falcone Miller and Miller 2010).

9 ESP: electrostatic precipitator; FGD: flue gas desulfurization.

10 Municipal waste, biomass, and some coals are fuels that may contain catalyst poisoning elements. They are thus less appropriate for a high-dust configuration.

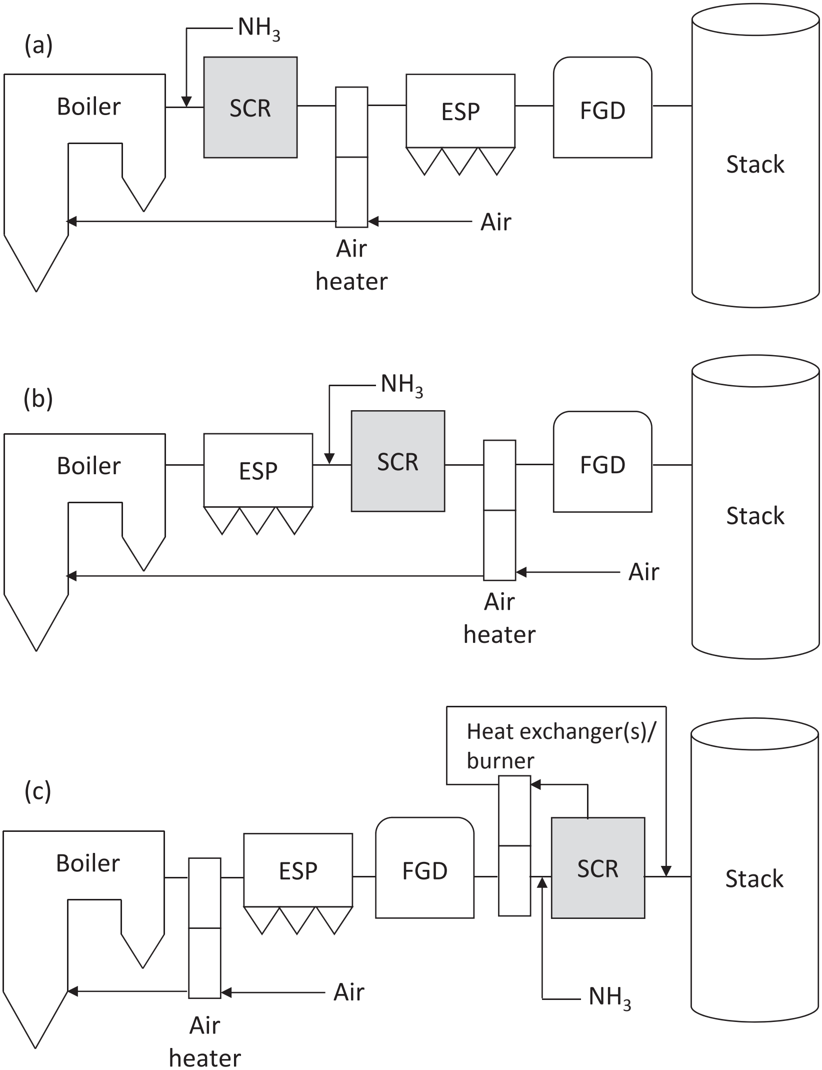

Figure 2-5: SCR configuration with typical system temperatures: (a) high-dust SCR, (b) low-dust SCR, (c) tail-end SCR (cf. Schreifels et al. 2012) [ESP: electrostatic precipitator; FGD: flue gas desulfurization].

Multiple issues need to be considered when designing SCR systems, such as fuel characteristics, catalyst and reagent selection and process conditions (Falcone Miller and Miller 2010). More information on several of these aspects will be provided in the following sections.

2.2.2.2 Reagent

US EPA (2016, 2-37) provides a detailed overview of the different reagents and their advantages and disadvantages. The most common reagents in use are ammonia (NH_3) and urea (CH_4N_2O). The reaction equations have been provided in section 2.2.2.1.

Ammonia is available as aqueous or anhydrous ammonia. Anhydrous ammonia is a gas at atmospheric temperature and consists of nearly pure ammonia. It is transported and stored under pressure and classified as hazardous material that usually requires special permits and safety measures (US EPA 2016). Aqueous ammonia is commonly transported and stored at a concentration of 29.4% ammonia in water. Its use reduces the safety effort, yet it requires more storage capacity and higher transportation costs due to the high share of water (US EPA 2016). Urea has the lowest safety requirements and a lower price than anhydrous or aqueous ammonia, yet it needs special on-site equipment to hydrolyze or decompose it into NH_3 before injection into the flue gas (US EPA 2016).

The type of reagent in use affects capital and operating costs. More cost relevant information will be provided in the calculation methodology in chapter 4.4.2.2. The most important selection criteria according to Heide (2012b) are availability, transport, storage, and costs as well as procedural aspects with regard to e.g. temperature and degree of mixing in the flue gas.

2.2.2.3 Catalyst and Catalyst Management

SCR catalysts may consist of various materials in manifold structures. A detailed overview would exceed the scope of this work. Common geometries are honeycomb or plate catalysts (Lecomte et al. 2017; Falcone Miller and Miller 2010). Catalysts usually consist of a ceramic or base metal carrier a barrier sheet and an active layer of metal oxides (e.g. V_2O_5, WO_3, TiO_2) (Falcone Miller and Miller 2010; Kolar 1990; Olsen et al. 2017; US EPA 2016).

Over time, all types of catalysts are deactivated by different mechanisms. The most influential parameters with regard to catalyst deactivation are the SCR system configuration (high-dust, low-dust or tail end) and the fuel characteristics. Of particular relevance regarding the fuel are the contents of alumina (Al_2O_3), ash, calcium (Ca), potassium (K), silica (SiO_2), sodium (Na), and sulfur (S) (Schreifels et al. 2012). The catalyst degrading mechanisms are erosion, plugging, poisoning, sintering and fouling. More details are provided in Schreifels et al. (2012) and Zheng et al. (2005). Particular substances and physical conditions that lead to catalyst deactivation and should thus be avoided are listed in Wiatros-Motyka and Nalbandian-Sugden (2018).

The deactivation of catalyst causes two major problems. The NO_X reduction rate decreases and at the same time, the amount of reagent that leaves the plant as such increases. This so-called ammonia slip enforces fouling and corrosion within the installations of the plant and is harmful to the environment when leaving the stack (Lecomte et al. 2017). Furthermore, the ammonia contaminates the fly ash, which is usually sold as by-product of (coal) combustion. Therefore, the ammonia slip is limited by local authorities via the operating permit and by contracts with the fly ash consumers (Wiesel et al. 2017).

Due to the complex degradation mechanisms and the strict limits for ammonia slip, an appropriate catalyst management is required in order to ensure reliable and cost-efficient use of the catalyst. According to Maier (2010), proper catalyst management should include:

- *"Flue gas monitoring with respect to SO_2 and NO_X upstream and downstream of the $DENO_X$ reactor, dust, temperature, CO and the like.(…) An increase in NO_X downstream of the $DENO_X$ reactor is a strong indicator for decreasing performance of the catalyst and (…) compensated automatically by an increase of ammonia injection (…).*
- *Ammonia-in-fly-ash measurement which is recommended to be analysed on a daily base (…). Due to ongoing exhaustion of the catalysts ammonia injection has to be increased and consequently increases the ammonia slip, which is detected by ammonia analyses of the fly ash (…).*
- *Activity checks are recommended to be performed once a year covering all layers of catalyst installed. The laboratory check (…) of the catalyst material (…) provide[s] a clear image of the catalyst status and enables the operator (…) to learn about the possible mechanisms of catalyst deactivation (…).*
- *Flue gas tracking is recommended once a year by determining the NO_X and NH_3 distribution downstream the SCR reactor to assure a proper distribution and to minimise the NH_3 slip behind the SCR. If necessary, the NH_3 injection grid has to be adjusted to equalise the NO_X pattern (…).*
- *At least once a year (…), the reactor should be visually inspected to recognise problems due to mechanical damage or flue gas/ash improper distributions at an early stage."* (Maier 2010)

Figure 2-6 displays an exemplary catalyst management plan. It starts with adding an additional layer as soon as the ammonia slip is close to the threshold of 2.0 ppm for the first time. Afterwards, the existing layers are replaced successively every time the ammonia slip approaches the threshold.

A common alternative to replacing exhausted catalyst with new catalyst is the regeneration of the catalyst. The regeneration process typically consists of two steps, the washing of the catalyst, i.e. the mechanical and/or chemical removing of fly ash and other deposits[11] and the reactivation of the catalyst using chemical solutions of active materials (McMahon 2006). A successful catalyst regeneration renews the activity up to between 90 % and 100 % of the activity of the original catalyst (Maier 2010).

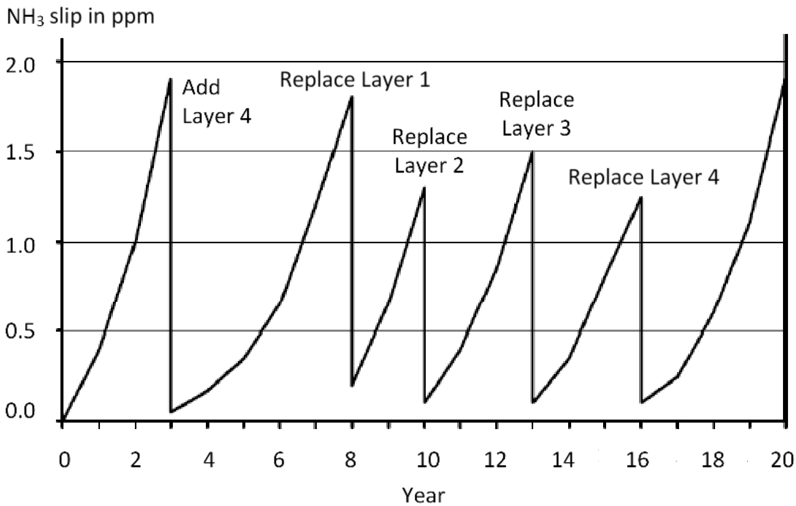

Figure 2-6: Exemplary catalyst management plan (US EPA 2016).

According to Maier (2010) catalyst regeneration has several advantages. It avoids increasing pressure drop that occurs when a new catalyst layer is added to maintain the necessary abatement efficiency because of deactivation of existing layers. It further reduces disposal costs for exhausted catalysts, which are often treated as hazardous waste, and the cost of regeneration is considerably lower than the cost of new catalyst (Maier 2010).

11 Depending on the fuel and combustion specifications, there are different compounds in the flue gas that may physically block or chemically poison the catalyst. This is especially critical in the case of biomass co-firing. More details are provided for example in Olsen et al. (2017).

The regeneration of catalysts and their protection against fouling elements and erosion is still an area of ongoing research and development. The most important developments over the last decades and during recent years are summarized in Olsen et al. (2017) and Wiesel et al. (2017).

2.2.2.4 Operation

An SCR system can be operated year-round or only in the ozone season in the summer months (US EPA 2016). For LCP, the emission limits in most parts of the world are comparably tight, so that year-round operation can be considered the regular case.[12] The operating scheme of the overall plant primarily influences the operation of an SCR by causing variations of the flue gas temperatures in case of part load operation. Old references such as Farwick and Rummenhohl (1993) and Rimmelspacher (1986) mention a minimum part load level of 40 % to 50 % that still allows SCR operation. Below this level, the flue gas needs to be preheated in order to enable the chemical reactions in the catalyst.

Newer installations might be slightly more flexible with regard to the temperature range of the flue gas due to specifically adapted catalysts. Yet the order of magnitude can be expected to be still valid, as confirmed by recent publications of Olsen et al. (2017) and US EPA (2016) that mention a recommended flue gas temperature of about 300 to 400°C at the catalyst. The influence of startup and shutdown cycles on SCR systems depends a lot on the fuel, combustion and boiler technology and size of the plant. Large coal-fired boilers may need 2 to 6 hours until the SCR becomes operational, in certain cases even up to 20 hours (Kokopeli et al. 2013). This may significantly influence the total NO_X emissions of a plant, particularly if startup and shutdown cycles become more frequent.

12 Due to the high investment for SCR systems, a seasonal operation becomes very unlikely, particularly as well-performing SNCR installation are available, which are significantly cheaper and can be expected to be sufficient for regions with higher emission limits.

2.2.3 Selective Non-Catalytic Reduction (SNCR)

The SNCR technology is less complex than SCR, as the chemical reduction of NO_X is based on a thermal reaction without catalyst. Otherwise, the chemical reactions (cf. eq. (2-6) to (2-8)) and the procedural principle remain the same. Higher reaction temperatures are necessary in order to enable the reaction between the reagent and the NO_X particles. Hence, the reagent is injected directly into the boiler at a flue gas temperature between 900 and 1050°C (Schultes 1996).

As reagent, the same substances can be used as for SCR. Due to the direct injection into the boiler, the selection of a suitable reagent depends more on procedural aspects such as depth of penetration, temperature ratio and degree of mixing in the flue gas (Heide 2012b). The chemical utilization rate of the thermal reaction between NH_3 and NO is a lot lower than for the catalytic reaction (approximately 30 %). This is caused by thermal decomposition of the reagent (IEA Clean Coal Centre 2017). Therefore, about two to three times the amount of reagent is needed to abate the same amount of NO_X particles using an SNCR compared to SCR (IEA Clean Coal Centre 2017).

In order to regulate the reagent injection according to the load level of the plant, different injection levels within the boiler are used. This is necessary to ensure injection in the optimal temperature range. If the flue gas is too hot, the injected ammonia will produce additional NO. In case it is too cold, the reduction reaction will not take place and hence cause ammonia slip (Wiatros-Motyka and Nalbandian-Sugden 2018). The number and range of injection levels determine the load flexibility of the SNCR system (Voje et al. 1991). Figure 2-7 displays an exemplary SNCR setup.

Due to its setup, the comparably small temperature range for reaction and the difficulty to execute real-time measurements of the physical properties of the flue gas at several locations in the processing chain, the SNCR technology is particularly prone to ammonia slip and needs to be closely monitored and precisely controlled (ICAC SNCR Committee 2008).

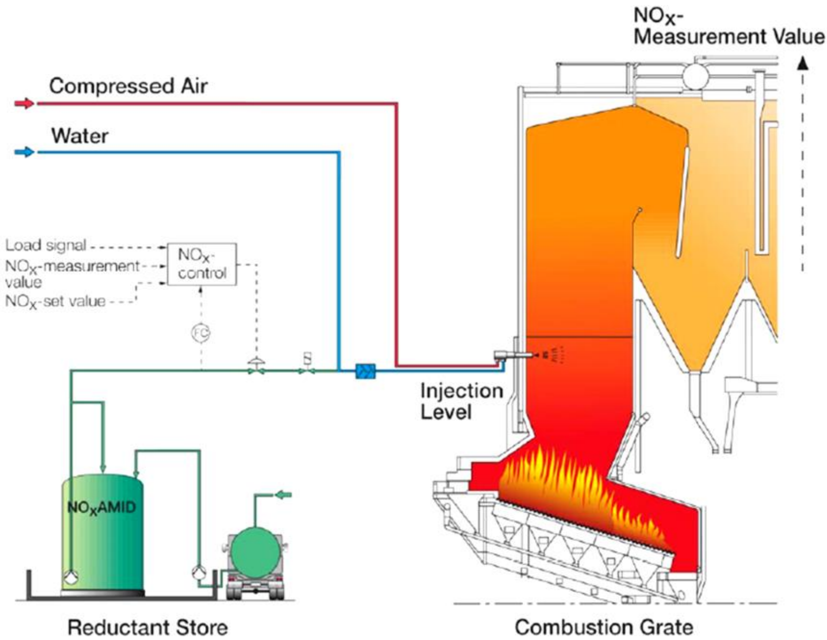

Figure 2-7: Process flow scheme of an SNCR system operated with aqueous ammonia (Heide 2008).

2.2.4 Emerging Techniques

Nowadays, the development of NO_X abatement techniques focusses primarily on the improving of existing technologies, with particular regard to their efficiency and their robustness against load variations and fuel impurity (Falcone Miller and Miller 2010).[13] Further progress is being made with regard to multi-pollutant systems, which abate more than one pollutant and hence reduce installation costs and space requirements of flue gas cleaning in general (Lecomte et al. 2017).

[13] Fuel impurity becomes particularly relevant with regard to biomass (co-)combustion.

A detailed description of emerging techniques in the field of NO_X abatement would go beyond the scope of this work. Nevertheless, a few references shall be mentioned that deliver more detailed and recent information. Apart from the BREF LCP (Lecomte et al. 2017), Wiatros-Motyka and Nalbandian-Sugden (2018) provide an overview of recently applied techniques with a special focus on the situation in India, a country that started comparably recently with the implementation of NO_X regulation. Sloss (2017) summarizes emerging techniques with a focus on retrofit installations and multi-pollutant abatement. Goldring and Riley (2016) focus on primary abatement techniques, while a detailed description of hybrid SCR/SNCR systems is available in Miller (2011). Another detailed, yet slightly older report was developed in 2012 in the context of TFTEI (Schulte Beerbühl and Hiete 2012).

Cost calculations for emerging techniques are highly technology dependent and may be complex, particularly in the case of multi-pollutant techniques. Therefore, they will not be assessed in further detail in the following, can, however, be regarded as an area of future work.

2.2.5 Abatement Potentials and Costs

Several references list abatement potentials for NO_X control measures. In the following, two examples are provided. Table 2-3 lists the fuel-specific abatement potentials of primary and secondary measures according to US EIA (2015). The values of other references differ slightly, the order of magnitude, however, is usually confirmed.[14]

[14] Cf. e.g. Lecomte et al. (2017), Goldring and Riley (2016) (the latter for primary measures).

Table 2-3: Average emission reduction rates for different types of fuels in large combustion plants (US EIA 2015).

Nitrogen oxides control technology	Coal	Oil	Natural gas	Wood
Burner out of service (staged combustion)	15%	15%	15%	15%
Low excess air	15%	15%	15%	15%
Biased firing (alternative burners)	15%	15%	15%	15%
Overfire air	25%	25%	25%	25%
Advanced overfire air	30%	30%	30%	30%
Low NO_X burners	45%	45%	50%	45%
Fuel reburning	55%	55%	55%	55%
SNCR	45%	33%	33%	55%
SCR	80%	80%	85%	80%
Ammonia injection	63%	56%	59%	68%
Flue gas recirculation	45%	45%	45%	45%
Water injection	15%	15%	15%	15%
Steam injection	15%	15%	15%	15%

Table 2-4 also provides ranges of reduction rates for LCP accompanied by the major technical limitations of the techniques. The ranges are comparably broad, as the achievable reduction depends not only on the technique but also on plant and fuel characteristics, particularly with regard to combustion control.

Table 2-4: Average reduction rates of selected primary and secondary NOx reduction measures for large combustion plants (UNECE 2015a).

Technique	Average NO_X reduction rate*	Technical limitations/ process risks
Low excess air	10-44%	Incomplete burn-out
Air staging (burner out of service, biased burner firing, overfire air)	10-70%	Incomplete burn-out
Flue gas recirculation	< 20% (coal) 30-50% (gas + OFA)	Flame instability
Reduced air preheat	20-30%	-
Fuel staging	50-60%	-
Air-staged LNB	25-35%	Incomplete burn-out Flame instability
Flue-gas recirculation LNB	<20%	Flame instability
Fuel-staged LNB	50-60%	Incomplete burn-out Flame instability
SCR	80-95%	Ammonia slip Contamination of fly ash by ammonia Air heater fouling
SNCR	30-50%	Ammonia slip which is usually higher than with SCR

* If several measures are applied, reduction rates are different

A cost comparison between the techniques will be provided in more detail in chapter 4, with a focus on secondary abatement techniques, as the costs of primary measures are particularly plant and process specific. A first summary is displayed in Table 2-5 that aims at setting the techniques in relation to each other, with primary measures causing considerably lower costs than secondary measures.

Table 2-5: Costs comparison of common NO_X reduction techniques for LCP (cf. European Commission 2006; Rentz 1979; Sinha 2016; Sloss 2017; Yelverton 2009).

Technique		Investment	Operating costs
Primary Measures	Low excess air Air staging Fuel staging Flue gas recirculation LNB	Low	Low, sometimes negligible
Secondary Measures	SNCR	Medium	Medium (power, reagent)
	SCR	High	High (power, reagent, catalyst)

2.2.6 Cross-Media Effects

Emission abatement measures of all kinds may not only influence their target pollutants but also other types of pollutants. In this context, direct effects are possible as well as indirect effects. Direct effects are the direct increase or decrease of other pollutants in the flue gas, e.g. by chemical subreactions. Indirect effects consider indirectly emitted pollutants, e.g. caused by the production of additional energy or other consumables that are necessary to operate the emission control installations. Several exemplary effects for primary NO_X abatement measures are listed in Table 2-6.

Table 2-6: Overview of cross-media effects from primary and secondary NO_X abatement installations (cf. Lecomte et al. 2017).

Technique	Cross-media effect
Low excess air	No information provided
Air-staging	**CO** may be formed and the amount of **unburnt carbon-in-ash** may increase. These drawbacks are limited in the case of boosted OFA systems, which enable intensive internal recirculation of flue-gases between the different combustion zones. Correctly designed OFA in new boilers will not result in high CO or high unburnt carbon. Air staging in the furnace may also increase the **energy consumption** in the case of boosted OFA, which typically requires dedicated booster fans.
Flue gas recirculation	FGR addition may slightly modify the heat exchange, with a minor increase in boiler flue-gas temperatures, resulting in a slight decrease in **energy efficiency** (e.g. 0.3 percentage points in the example plant case). Tendency to lead to higher **unburnt carbon-in-ash**.
Reduction of combustion air temperature	Lowering the air preheat temperature results in higher **fuel consumption**. This can be counterbalanced by e.g. increasing the size of the economizer.
Fuel staging	When using coal or oil as reburning fuel, nitrogen is present in a certain quantity, leading to **NO_X formation** in the burnout zone. This drawback can be reduced or avoided by using natural gas.
LNB	As the pressure drop in air ducts increases in comparison with standard burners, it may result in higher **operational expenses**. E.g., coal pulverization may have to be improved. The level of **carbon-in-ash** may increase. The addition of classifiers to the coal mills is an efficient way to counterbalance this problem. Modern coal LNB are efficiently designed not to influence the carbon-in-ash level. LNB may also increase **CO** generation due to cooler, larger flames. This generation will increase at low loads.

Literature with regard to cross-media effects of NO_X abatement is comparably scarce.[15] Nevertheless, the BREF LCP (Lecomte et al. 2017) provides a recent overview. The most relevant effects of secondary abatement measures are summarized in the following. This overview shall not be regarded as an exhaustive list, because some more effects may occur depending on the technical configuration of the plant and its operating strategy.

For SNCR systems, the most relevant direct cross-media effects are summarized as follows, according to Lecomte et al. (2017):

- The formation of **nitrous oxide (N_2O)** may be influenced, particularly when injecting urea directly into the boilers. To overcome this problem urea can be injected into the burnout air.
- **NH_3** may be released to air, in the case of inhomogeneous reactions between NO_X and NH_3 (ammonia slip).
- **Ammonium sulphates** may be formed when sulfur-containing fuels such as liquid refinery fuels are in use.

For SCR systems, the issues summarized below are considered most critical:

- **NH_3** may be released to air, in the case of inhomogeneous reactions between NO_X and NH_3 (ammonia slip).
- **Ammonium sulphates** may be formed in case of incomplete reaction of NH_3 with NO_X, which are deposited on downstream systems such as the catalyst and air preheater and the NH_3 concentration in the fly ash may increase. This incomplete reaction, however, only occurs in the unlikely case of major failures of the SCR system.
- The reaction from **SO_2 to SO_3** may be enforced. This effect can be reduced by advanced catalyst manufacturing (ICAC 2009).

15 Other emission abatement installations cause a significantly higher cross-media impact and are hence better investigated in science and practical publications.

- Low load operation can cause problems with maintaining the minimum temperature, which may result in the condensation of **ammonium bisulphates (ABS)**. ABS is a highly acidic and sticky substance that can deposit on the catalyst and downstream equipment and cause further negative effects (e.g. ammonia slip).
- The flue-gas pressure drop caused by the catalyst unit requires additional **energy** to be offset. Furthermore, in the tail-end arrangement, reheating may be needed for the catalyst to reach the minimum operating temperature (Lecomte et al. 2017).

The information above displays that there are hardly any effects, which are systemic and can hence not be reduced or avoided by operating management and/or technological improvements.

Secondary pollution is primarily caused by emissions of electricity generation. As these emissions occur directly within the considered plant, they shall be further assessed in the following (cf. 4.6.4).[16] Other secondary emissions, caused e.g. by the production of the reagents or catalysts shall not be considered, as they occur externally and are expected to be considered in the pricing of these goods.

2.3 Environmental Policy Measures

Various political instruments have been implemented all over the world in order to reduce emissions in general and NO_X emissions of the energy sector in particular. An overview will be presented in the following, aiming at providing a comparison of international legislation and key drivers for successful emission abatement. This information is particularly but not exclusively of

[16] This statement assumes that the plant consumes its own energy, which technically does not always have to be the case, but from an economic point of view, it can be considered a reasonable assumption.

interest for political entities, especially in developing countries. The national regulations of a broad range of countries with regard to NO_X emissions of the energy sector will be displayed and investigated qualitatively and quantitatively. More general information on environmental policy is provided by e.g. Baldwin et al. (2012), Böcher (2012), Böcher and Töller (2007), Breun (2016), Breun et al. (2012) and Callan and Thomas (2013).

Beyond 'standard' policy discussions, there are new influences such as private environmental finance schemes starting to be discussed in literature (cf. Langer 2015). Yet, due to lacking practical experience, they will not be considered in the following.[17]

2.3.1 Political Instruments

Policy Instruments for environmental regulation can be grouped in two to four main categories. Command and control measures and economic incentives are the two most important categories (Baldwin et al. 2012; US EPA 2005). Some references mention a third and fourth category, the so-called informational or persuasive instruments (cf. Breun 2016; Michaelis 1996) and the cooperative instruments (Böcher 2012; Böcher and Töller 2007). Typical examples for informational instruments are labels for customers (e.g. eco-labels) or publicly available data sources, such as the data collected by national or international PRTR[18]. Examples of cooperative instruments are roundtables, mediation, certifications, and voluntary agreements. Cooperative instruments shall not be regarded in further detail in this work, as they are very diverse and sector specific. Therefore, general conclusions are hardly

[17] Major parts of this chapter have already been published in Mayer et al. (2016). Contents of this chapter that are not quoted were exclusively prepared by the author of the book at hand.

[18] PRTR: Pollutant Release and Transfer Register. These national or international (e.g. EU) registers provide easily accessible key environmental data from industrial facilities. According to the European Environment Agency (2018b), the register contributes to transparency and public participation in environmental decision-making.

possible. Informational instruments shall be handled according to the approach of US EPA (2005): due to the major economic influence that can be caused by customers[19], informational instruments are categorized as a subgroup of economic incentives. The two resulting categories, command and control instruments and economic incentives will be introduced below.

2.3.1.1 Command and Control (C&C) Instruments

Command and control (C&C) instruments are the most traditional way of setting limitations for the environmental impact of industrial operation. *"The essence of command and control (…) regulation is the exercise of influence by imposing standards backed by criminal sanctions. (…) The force of law is used to prohibit certain forms of conduct, to demand some positive actions, or to lay down conditions for entry into a sector."* (Baldwin et al. 2012, p. 106).

A typical example that will be presented in more detail in the following is emission limit value (ELV) regulation for the emission of pollutants to air. The main advantage of C&C regulation is its general and immediate validity and unambiguity (Baldwin et al. 2012). A plant operator or investor knows in detail which target values need to be met (sometimes even how they need to be met) without facing major uncertainties.[20] Moreover, it is a strong instrument for political entities as it is based on the force of law (Baldwin et al. 2012; Callan and Thomas 2013). It further allows a comparably easy estimation of the environmental effects of regulation, if the considered sector is well controlled and monitored.

Nevertheless, certain sectors (particularly those with many small operating entities) are difficult to manage and control and the definition of appropriate regulation for all parties involved may be challenging, if not impossible. The

[19] Customers are not exclusively but primarily addressed by this group of instruments.

[20] This does not refer to the uncertainty of changing regulation, but to the economic uncertainty of monetary policy instruments.

largest and probably most diverse group of actors are consumers. Furthermore, the agricultural and the transport sector, both characterized by manifold (small) entities, are difficult and expensive to handle (US EPA 2005).

An important disadvantage of C&C regulation is the missing incentive to improve processes beyond the required limits (US EPA 2005). Therefore, starting in the 1980s, an increasing group of politicians and economists promoted the application of economic incentives in order to fortify or replace traditional C&C methods (Baldwin et al. 2012; Böcher 2012; Callan and Thomas 2013).

In the context of this work, the group of C&C instruments can be further separated in three subgroups: emission and immission limit values and best available techniques (BAT). An introduction and a brief assessment will be provided in the following.

2.3.1.1.1 Emission Limit Values

The most common way to regulate NO_X emissions of the energy sector is emission limit values (ELV). ELV are set for stack emissions, usually in milligram per normal cubic meter of flue gas (other units such as parts per million are used in some parts of the world but are less common). ELV regulations are often rather complex – they vary for different fuels, technical configurations, installation capacities, industrial sectors, times of installation, etc. and may include various exceptions.

ELV are typically derived from international air quality standards, so that the total industrial activities in a country or region influence the values as well as the activities within the regarded sector. The limits can be set by international (e.g. EU), national or regional/local authorities (Baldwin et al. 2012). To give an example, Table 2-7 lists the limit values in Annex V of the 2012 amendment of the so-called Gothenburg Protocol (UNECE 2013) for NO_X emissions from solid-fueled LCP.

Table 2-7: NO_X ELV for solid fueled stationary sources in the 2012 Amendment of the Gothenburg Protocol (UNECE 2013).

Thermal input (MW_{th})	Plant type	ELV for NO_X (mg/m³)
50-100	New plants	300 (coal, lignite and other solid fuels)
		450 (pulverized lignite)
		250 (biomass, peat)
	Existing plants	300 (coal, lignite and other solid fuels)
		450 (pulverized lignite)
		300 (biomass, peat)
100-300	New plants	200 (coal, lignite and other solid fuels)
		200 (biomass, peat)
	Existing plants	200 (coal, lignite and other solid fuels)
		250 (biomass, peat)
>300	New plants	150 (coal, lignite and other solid fuels)
		150 (biomass, peat)
		200 (pulverized lignite)
	Existing plants	200 (coal, lignite and other solid fuels)
		200 (biomass, peat)

2.3.1.1.2 Immission Limit Values

Immission limit values are directly based on the idea of compliance with air quality standards: a plant needs to prove that it will not cause a noncompliance with air quality standards in the surrounding area. Hence, the total emissions of the plant are relevant as well as the present air quality in order to get a permit for operation. Hence, it is an impact-based instrument, which causes severe effort, as every plant needs to be regarded separately. Furthermore, it creates uncertainty during the planning stage, as investors might not know if the plant will get a permit in the designated manner, for example, if the immission loads of surrounding sources are not known. In order to assess the advantages and disadvantages of emission and immission limit values, Table 2-8 provides an overview of strengths, weaknesses, opportunities, and threats (SWOT) for both, emission and immission limit regulation.

Table 2-8: SWOT-analysis of emission and immission limit regulation.

Strengths	Weaknesses
Emission limits: • Transparency for investors and/or plant operators • Equality and neutrality among different regions, companies, etc. • Easy to monitor/supervise Immission limits: • Consideration of local circumstances • Possibility to find individual solutions • Focus on air quality results in minimum negative influencing of humans and the environment	Emission limits: • No incentive for plant operators to lower emissions below the ELV • Low adaptability towards local, organizational and technical circumstances • Complex and detailed regulation Immission limits: • No incentive for plant operators to lower emissions below the limit • High management effort • Low predictability for investors • Difficulty and high effort to measure local air quality
Opportunities	**Threats**
Emission limits: • Achieving national emission ceilings by implementing a functioning control and penalty mechanism • Early announcement of changes in regulation enables plant operators to react on time and in a technically and economically reasonable way Immission limits: • Focus on achieving air quality standards throughout the country without overburdening industry and economy • Reasonable local arrangement of emitters can be achieved • Support for less developed regions	Emission limits: • Local exceeding of air quality limits, if many installations are situated nearby • No incentive to set up emitting installations outside critical regions (i.e. cities) • Unexploited abatement potentials if ELV are not sufficiently stringent or detailed Immission limits: • Difficulty to reliably forecast local immission from emission data • Focus might shift from abating emissions to finding a suitable location • Unexploited abatement potentials if plants are situated in regions with good air quality

2.3.1.1.3 Best Available Techniques (BAT)

Another example of C&C regulation is the enforcement of Best Available Techniques (BAT).[21] The use of these techniques (in the EU defined in several sector-specific BREF[22]) is mandatory for new installations to get a permit to operate and existing plants may have to be retrofitted according to amended regulation (Lodewijks et al. 2013). An exemplary BREF is the LCP BREF (Lecomte et al. 2017).

The aim of BAT regulation is to ensure the most reasonable selection and design of industrial installations (from a techno-economic-ecological perspective). The Gothenburg Protocol also refers to the concept in Article 3: "*Each Party should apply best available techniques to mobile sources covered by annex VIII and to each stationary source covered by annexes IV, V, VI and X, taking into account guidance adopted by the Executive Body*" (UNECE 2013, p. 9). A detailed definition of BAT is provided in Table 2-9.

Table 2-9: Definition of BAT in the Industrial Emissions Directive (IED) (Chronopoulos 2016).

Best	Most effective in achieving a high general level of protection of the environment as a whole
Available	Developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions
Techniques	Both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned

[21] BAT is the EU name for the concept, other countries or regions may have different names, the concept, however, is usually similar.

[22] BREF: Best Available Techniques Reference Document.

The BREF documents are a vast body of knowledge. Therefore, the main aspects and particularly the binding constraints for industrial plants are summarized in the BAT conclusions. In order to quantify the performance of BAT, the so-called BAT-AEL (BAT Associated Emission Levels) are provided in the BAT conclusions. These levels are mandatory for plants in the given sector and are particularly relevant for comparison if other than the described BAT shall be applied.[23] Table 2-10 provides exemplary BAT-AEL for solid fuel combustion in LCP. A discussion of the impacts of the amended BAT regulation for LCP with special regard to Germany is provided by Ahrens (2017).

Table 2-10: BAT-associated emission levels (BAT-AEL) for NO_X emissions to air from the combustion of coal and lignite in LCP. FBC: Fluidized Bed Combustion, PC: Pulverized Coal (Lecomte et al. 2017).

Combustion plant total rated thermal input (MW_{th})	BAT-AEL (mg/Nm³)			
	Yearly average		Daily average or average over the sampling period	
	New plant	Existing plant (*)	New plant	Existing plant (*)
< 100	100-150	100-270	155-200	165-330
100-300	50-100	100-180	80-130	155-210
≥ 300, FBC boiler combusting coal and/or lignite and lignite-fired PC boiler	50-85	< 85-150 (*)	80-125	140-165 (*)
≥ 300, coal-fired PC boiler	65-85	65-150	80-125	< 85-165 (*)

(*) Further remarks are provided in the original reference (Lecomte et al. 2017, p. 758)

23 It is possible to use other techniques than BAT, yet it needs to be proven that the alternative technique achieves an equal or higher level of environmental protection than BAT.

An innovative alternative to setting emission limits or BAT by policy committees is the top-runner program implemented in Japan for energy efficiency improvement in several sectors. The aim is to derive industry targets from the best performing product or plant (top-runner). A certain factor of the top value is defined as the minimum average level for competitors. This approach supports constant technological improvements without the need to amend existing regulation regularly. Detailed information is provided in METI (2015).

2.3.1.2 Monetary Instruments

US EPA (2005) provides an overview of the most relevant economic incentives as well as international application examples and experiences thereof. The document considers the following types of instruments:

- Pricing mechanisms including fees, charges, and taxes
- Deposit-refund systems and performance bonds
- Pollution trading systems
- Subsidy systems including grants, low-interest loans, favorable tax treatment, lending practices of international banks, preferential procurement policies
- Removal of environmentally harmful subsidies
- Liability for compensating victims when sources release pollution that causes harm to human health and the environment
- Information disclosure
- Voluntary measures and non-monetary rewards (US EPA 2005).

In the context of this work, not all instruments are of equal relevance. Most relevant are considered all sorts of pricing mechanisms and pollution trading systems, as well as subsidy systems and removal of subsidies. Liability may become more relevant in future discussion. Currently, however, this issue plays a less important role. Informational and voluntary measures are certainly relevant, yet they are difficult to be monetarized due to their sector, region, and application specific aspects.

In general, economic incentives aim at encouraging polluters to reduce their emissions rather than forcing them to follow a particular rule (Callan and Thomas 2013). In this context, the 'polluter-pays principle' is mentioned, which aims at making the polluters pay for the caused damage. Therefore, an incentive for pollution prevention based on the forces of market is created (Callan and Thomas 2013).

The qualitative statements of US EPA (2005)[24] can be complemented by Stavins (2003), who provides qualitative and quantitative data on market-based environmental policy instruments. Furthermore, the report of OECD (2013) compares carbon prices resulting from different economic incentives for the energy sector. Unfortunately, recent quantitative publications are scarce. This may be caused by the complexity and dynamics of international policy, which makes it hard to compare specific instruments in different countries. A short introduction on the most commonly used economic incentives in the energy sector, with particular regard to NO_X abatement, is provided in the following.

2.3.1.2.1 Taxes and fees

Taxes for NO_X are not very common in an international context. Nevertheless, there are some interesting examples such as the system implemented in Sweden. Plant operators have to pay a tax per kilogram of NO_X emitted that is combined with a refund mechanism per MWh electricity generated. More details are provided in Naturvårdsverket (2006). Plants with low NO_X emissions and high energy output are net recipients, whereas installations with higher emissions per energy output are the net payers. Goal and main advantage of this instrument is to achieve the minimum reasonable emissions, even below the applicable ELV. A difficulty of the mechanism is the extensive control, surveillance and administration effort (Naturvårdsverket 2006).

[24] This analysis has a general perspective and is not specifically adapted to the given sector and type of application (NO_X abatement in LCP).

The Canadian government published a statement that is more critical about direct fees and taxes: "*A tax on air pollutant emissions would have different effects in different regional contexts, as firms chose whether to pay the tax or invest in abatement equipment, and so no emissions floor could be guaranteed. Since the quantity of emissions reductions cannot be controlled with a tax, this instrument is better suited when an incentive to continually reduce emissions is sought*" (Department of the Environment and Department of Health 2014, p. 1333). This declaration directly leads to the conclusion that a combination of regulatory instruments (in this case emission limits and an emission tax) seems to be appropriate for countries aiming at constantly reducing emissions.

2.3.1.2.2 Subsidies

The results of the research regarding financial support programs were rather scarce. South Korea published information about a Low-NO_X-Burner program (Ministry of Environment ROK 2012), whereas the Canadian government again does not support these initiatives as they might set wrong impulses and "*would be inconsistent with the 'polluter pays' principle*" (Department of the Environment and Department of Health 2014, p. 1333). The small number of exemplary financial support programs discovered may be caused by the fact that such programs are often very complex, country-specific (and hence published in local languages) and may target not only pollutant control systems. Therefore, specific research would be necessary to depict the current international situation thoroughly.

2.3.1.2.3 Market-based instruments

Certificate trading is an instrument, which is well known for CO_2 and other greenhouse gas emissions within the EU, but also in other regions of the world. There is a lot of research going on regarding the impacts of certificate trading, cap-and-trade markets and other implementations of market-based emission control policy for greenhouse gases (cf. Aulisi 2005; Carmona et al. 2010; European Commission 2013; Firger 2015; Hoffmann 2007; Insley 2003; Laurikka and Koljonen 2006; Sarkis and Tamarkin 2005; Zhang and Wei 2010).

Cap-and-trade markets for NO_X were or are still implemented in a few regions worldwide. One example is the RECLAIM program in the South Coast Air Basin area around Los Angeles, USA. This area faced severe problems with smog and therefore implemented a certificate market for NO_X and SO_2. More details are provided by South Coast AQMD (2018). More examples of regional NO_X markets in the USA are provided by Callan and Thomas (2013).

The Netherlands also implemented a certificate market for NO_X in 2005, in addition to existing EU regulation. The program, however, was stopped in 2013 due to a NO_X price close to zero. Amended EU C&C regulation led to massive reductions of NO_X emissions so that the certificate market was undermined and ineffective (Jonge; Könings 2003).

This example shows that a vertical integration of policy measures is possible. However, the design of the instruments needs to be harmonized and adjusted in order to ensure an effective interaction of instruments. Otherwise, policies may be ineffective and their administrative effort outweighs their gains (Robertson 2016).

The EU Commission also discussed the implementation of an EU wide NO_X market, as proven by a report published in 2010 (European Commission 2010). Since then, however, no prominent efforts in this direction have been known, probably due to the difficulties described above. Therefore, in a mid-term perspective, the implementation of a NO_X market in the EU can be considered rather unlikely.

2.3.2 Status of International Policy

Several of the policy instruments mentioned above are in use for reducing NO_X emissions. A comprehensive overview of international NO_X policy for the energy sector is difficult, as there are many influencing parameters and varying definitions of sectors and techniques. Furthermore, the research is hindered by the broad variety of local languages and offline information that is hardly accessible from abroad. A helpful database for international applications of policy instruments is provided by OECD (2018b). This database, however, cannot be directly searched for NO_X abatement policy. Therefore, an overview will be provided in the following.

Starting with the example of the EU, which displays the complexity of international regulation by many interacting instruments, a global dataset will be provided and assessed for two exemplary installations of the energy sector.

2.3.2.1 Framework of EU Regulation

Figure 2-8 displays the framework of air pollution regulation in the EU with the key regulating entities. This figure is not to be regarded as a complete list of regulations for the energy sector, as there are further international influencing entities, such as the UNFCCC with its COP agreements.[25] An overview of current regulation in the EU member states outdates rapidly, as it is not only EU but also country specific. Therefore, a brief overview of the historical development of EU regulation based on Lodewijks et al. (2013) is provided in the following, neither claiming exhaustiveness nor the latest actuality.

In 1988, the "*Council Directive 88/609/EEC on the limitation of emissions of certain pollutants into the air from large combustion plants*" (EEC 1988) was enacted. This directive was in force until 2001 when the EU LCP Directive (LCPD) 2001/80/EC (EU 2001) was agreed on. Therein, emissions of three pollutants (SO_2, NO_X, and PM) are regulated and the deadline for adoption in national legislation of the EU member states was November 2002.

[25] COP: annual Conference of the Parties of The United Nations Framework Convention on Climate Change (UNFCCC). More information on the Convention and the Conferences are provided on the website: UNFCCC (2014). An overview of further international agreements with a focus on the USA is provided by Callan and Thomas (2013).

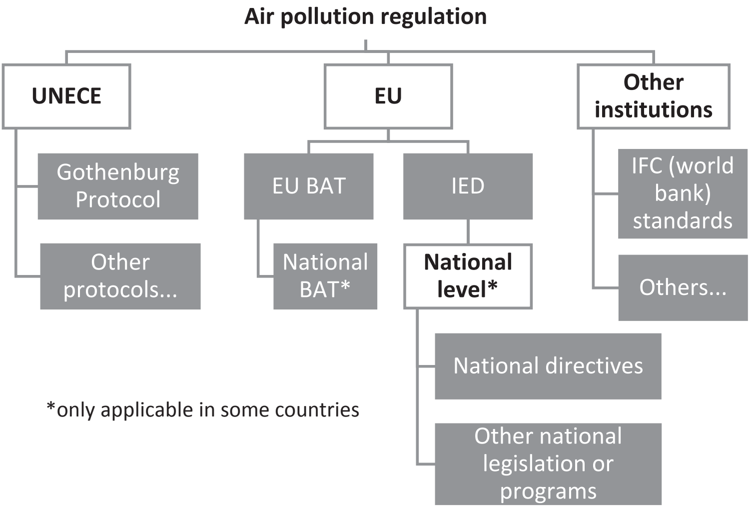

Figure 2-8: Exemplary overview of the emission regulation scheme in the EU .

LCP are also regulated under the Integrated Pollution Prevention and Control (IPPC) Directive (EU 2008) which may lead to stricter and/or additional obligations on the plants than those required under the LCPD itself. In particular, the IPPC Directive enforces the application of BAT. In 2006 the European Commission adopted the LCP BREF (European Commission 2006) including the BAT-AEL. The IPPC Directive and the LCPD were superseded by the Industrial Emissions Directive (IED) (EU 2010) which came into force on 6 January 2011 and which had to be transposed into national legislation by 7 January 2013. The IED regulates emissions from LCP by requiring the application of BAT and the BAT-AEL, as well as by setting mandatory 'minimum' emission limit values (ELV) for SO_2, NO_X, and dust. These limit values apply for existing combustion plants from 2016 onward, with some longer transitional periods for particular groups of plants. The LCP BREF was further amended in 2017, again lowering the BAT-AEL for NO_X (Lecomte et al. 2017). These values are currently the lowest emission limits for NO_X in EU wide regulation.

2.3.2.2 Examples of International Regulation

Due to the diversity of international regulation, two exemplary installations were selected in order to assess international policies. A 1 000 MW coal-fired boiler is selected as the first example, representing the category of large base-load installations. Furthermore, a 100 MW gas turbine shall be investigated in order to compare installations of different size and fuel. Both installations are expected to be new so that the most recent regulation applies.

The Table in Annex A sums up the results of the research. It displays 28 non-EU countries and the EU with their ELV (if applicable) for the selected examples. Due to the difficulties in information gathering regarding less common policy instruments, only emission and immission limits are displayed. Examples of other political instruments have been mentioned above, yet they are usually not applied separately but in combination with either emission or immission limits. Furthermore, the technical conditions or units vary. Especially the reference oxygen concentration defers for some countries or the documents do not provide it so that the given values have to be regarded as approximate values. The list is not exhaustive, as additional regulation may apply, which was not identified during the survey.

In developing or emerging countries, NO_X emission regulation seems to be in its infancy, even though it was difficult to gather significant data for these countries. Language issues and the fact that countries would not publish legislation that does not exist complicate a definite statement. Nevertheless, most countries have general air quality limits, often based on the WHO (World Health Organization) recommendations (WHO 2018). This is the first step towards actually managing and reducing emissions. Furthermore, the World Bank Group (IFC) sets up its own emission guidelines for projects in order to receive funding, which may influence new projects in these countries beyond local legislation (International Finance Corporation 2008).

The survey of existing political regulation provides a broad range of ELV for the two examples displayed in Figure 2-9. The range might be even larger if other political instruments were also taken into account. It may seem surprising that China – well known for air pollution and smog issues – has very stringent emission regulation. This could be caused by the severe problems with air pollution the country faces every day and the thereof resulting obvious need to reduce emissions. Furthermore, China updated its NO_X emission regulation comparably recently, whereas the regulations of other countries have been in force for many years or even decades and seem to be rather outdated (ChinaFAQs 2012). Another open question is the extent to which ELV are not only set up but also met and monitored. Some countries publish penalties and fines for exceeding ELV. Nevertheless, it is often unclear how strict they are handled in practice.

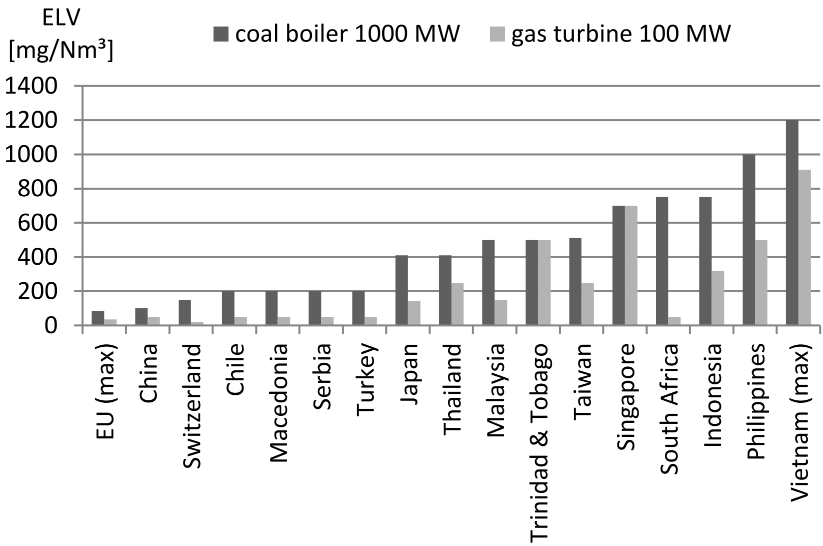

Figure 2-9: Comparison of international NO_X regulation for two exemplary installations. The countries with complete datasets are included; the EU member states are combined as EU-28. If a range of ELV is given, the maximum values have been chosen and marked with (max) (for references: cf. Annex A).

2.3.3 Results and Effects of EU Policy Campaigns

In order to assess the effectiveness of environmental policy in the EU, the associated emission statistics will be analyzed in the following. An international comparison of current national legislation and emission statistics is difficult, as several aspects and definitions (may) vary.[26] Therefore, this section focusses on the EU, as the development of policy regulation was identical or at least similar for all member countries over the last decades.

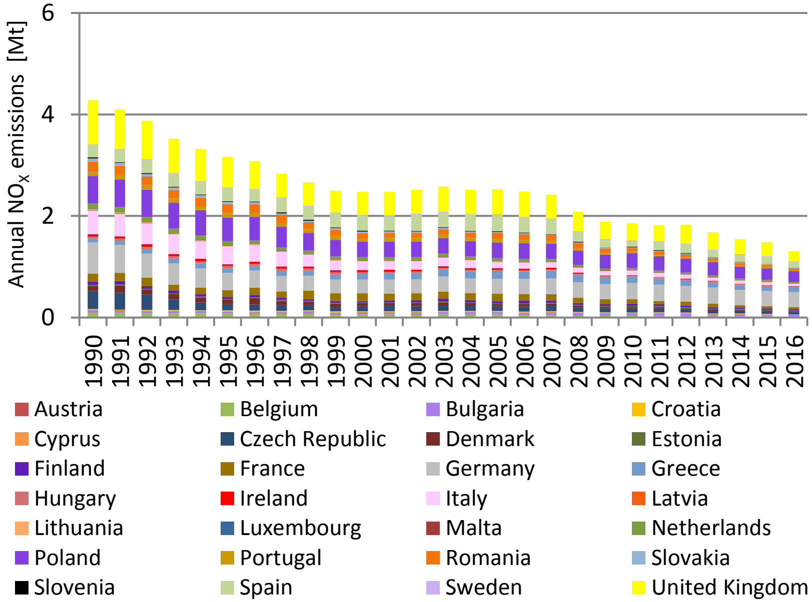

Figure 2-10: Total annual NO_X emissions of the energy sector (sector definition: energy production and distribution) per country within the EU-28 between 1990 and 2016 (European Environment Agency 2018a).

26 E.g. the definition of sectors, physical units, reference values etc.

Figure 2-10 displays an overall decline of NO_X emissions of 69 % between 1990 and 2016. Yet, between 1999 and 2007, the total emissions hardly declined but even increased slightly. In order to analyze this development, it is necessary to take the total amount of energy generated from NO_X emitting fuels into account. Figure 2-11 provides this data for the same countries in the time span between 1990 and 2016.

The largest increase in electricity generated from NO_X emitting fuels occurred between 1997 and 2007. Thus, the time span of this increase correlates with the lowest decline in total emissions and provides a possible explanation for the total emission development during this period.

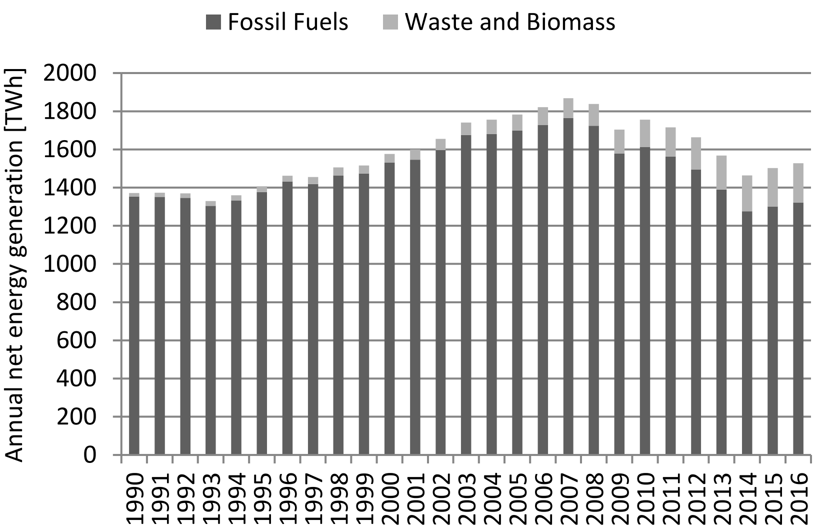

Figure 2-11: Annual net electricity generation from (main) NO_X emitting fuels within the EU-28 between 1990 and 2016 (US EIA 2018).

In order to scale the total emissions, Figure 2-12 displays the specific NO_X emissions in kg per MWh electricity generated from NO_X emitting fuels. It is compiled from the data of Figure 2-10 and Figure 2-11 and displays a nearly constant decline of specific emissions. Only in the period between 2010 and 2012, the specific emissions increased slightly.

Every new EU Directive that came into force aimed at lowering total NO_X emissions of the energy sector by setting emission limits for new and existing installations. The largest relative abatement success took place between 1993 and 2000. Hence, it started five years after the entry into force of the 1988 Directive and according to Brandwood (9/27/2018), this was the first phase of technical NO_X emission abatement when particularly primary measures were installed in a large number of plants.

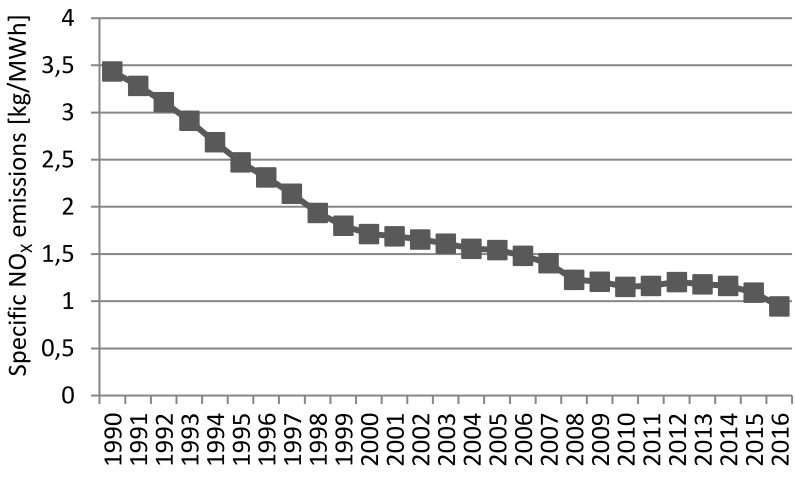

Figure 2-12: Specific NO_X emissions in kg per MWh electricity generated from NO_X emitting fuels within the EU-28 between 1990 and 2016.

Furthermore, the long approval and construction times of NO_X abatement installations led to a time lag between the entry into force of regulation and the actual compliance of industry. Depending on the details and stringency of the regulation, existing plants usually have an adaptation time until they need to be retrofitted with emission abatement installations.

The decline of relative emissions after the successive EU directive in 2001 was a lot lower. This might lead to the assumption that this directive was less successful. On the other hand, it can be expected that until 2000 the majority of plants was equipped with (at least primary) emission abatement installations so that even the newer regulation might have been fulfilled already. Moreover, further emission abatement became more expensive and technically more challenging. The additional emission abatement that is technically and economically feasible and arguable for plant operators is thus lower than before and leads to decreasing reduction rates.

Another fact that needs to be considered is the admission of new member states to the EU. The EU-28 countries are considered for this investigation, yet by 1990, only 12 countries were member states of the EU. In 2004 the EU consisted of 25 member states. These countries had to lower their emissions during the 1990s and early 2000s in order to fulfill European legislation and to be accepted as a member state of the EU. Hence, this might be another influencing factor for the high reduction rate between 1990 and 2000.

After the implementation of the 2010 Directive, the relative emissions increased slightly. There is not yet a direct explanation for this short period between 2010 and 2012. It will be interesting to assess this trend in detail in further studies.

The validity of the numbers presented above is limited by the fact that the sector definitions vary between the data of Figure 2-10 and Figure 2-11 as they are based on different references. Figure 2-10 contains data of the sector 'energy production and distribution' whereas Figure 2-11 refers to 'net electricity generation'. As the region and time span considered are relatively broad, the error caused by this issue is considered acceptable, particularly as this work aims at discovering trends and overall developments rather than providing a precise quantitative assessment.

2.4 Conclusions

The chapter at hand introduced important aspects of NO_X emissions from the energy sector. Starting with the characteristics and formation mechanisms of NO_X in LCP, abatement strategies for technical emission reduction technologies were derived. A brief introduction of primary and secondary NO_X abatement installations offers the basis for the associated cost calculation methodology in chapter 4. Finally, an overview of policy instruments with regard to NO_X abatement was provided. The comparison of different policy instruments showed that there is no clear preference for one or another. As important as the chosen instrument itself appeared to be its proper selection (according to the applying circumstances), its implementation and management and its interference with other political instruments.

The following chapter 3 complements the fundamental knowledge with a brief assessment of industrial decision-making in general, for environmental investments in particular and with a special focus on decision-making under uncertainty. Hence, chapters 2 and 3 form the base ground for the development and implementation of the techno-economic and the ROA model in chapters 4 and 5.

3 Decision-Making for Environmental Investments

Investment calculation and decision-making for emission abatement installations in large combustion plants are particularly complex due to the long-term perspective and many influencing risks and uncertainties.[1] Consequently, an examination of risks is considered necessary in order to derive reasonable investment decisions. By comparing classical project and risk management approaches[2] with the experiences from plant operators and the technological characteristics of emission abatement in LCP as well as standard decision-making models[3], the six steps approach displayed in Figure 3-1 was developed and initially published in Mayer et al. (2017).

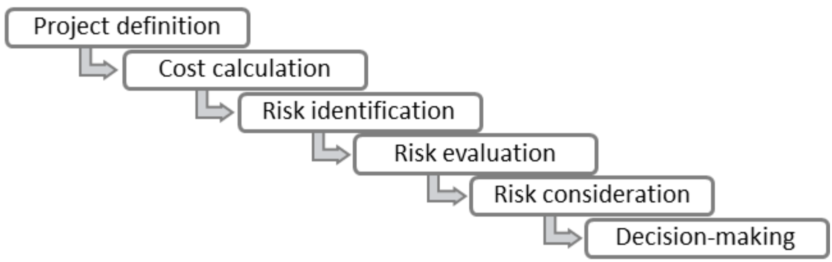

Figure 3-1: Decision-making approach for environmental investments

1 In the following, the terms 'risk' and 'uncertainty' are used synonymously. A further definition and discussion thereof will be provided in section 3.3.
2 E.g. Epstein and Rejc Buhovac (2014), Hubbard (2009), Project Management Institute (2008).
3 E.g. the intelligence-design-choice model of Simon (1977), cf. also Schätter (2016).

The chapter at hand is structured according to this approach. Section 3.1 refers to project definition with a special focus on different types of environmental investments. Section 3.2 assesses the calculation of investments and operating costs in the context of environmental investments. Identification, evaluation, and consideration of risks and uncertainties are discussed in section 3.3 and different investment appraisal methods are introduced in section 3.4. Section 3.5 provides an overview of the real option analysis as a method to evaluate uncertain investment decisions and section 3.6 summarizes the application specific conclusions and the research questions for the model implementation in the chapters 4 and 5. [4]

3.1 Types of Environmental Investments

Götze et al. (2015) define an investment in general: *„An investment project is a series of cash inflows and outflows, typically starting with a cash outflow (the initial investment outlay) followed by cash inflows and/or cash outflows in later periods (years*).” (Götze et al. 2015, p. 3).

Furthermore, several subtypes of investments exist. One exemplary classification for environmental investments is provided by Klingelhöfer (2006) with the following three types of investments:

- Investments to fulfill environmental regulation
- Investments, which are fully or partly committed to environmental protection
- Other investments with positive environmental impact (beyond the original intention of the investment) (Klingelhöfer 2006, p. 9).

[4] Parts of this chapter have previously been published in Mayer et al. (2017), Mayer and Schultmann (2017) and Schiel et al. (2019).

A second classification is also introduced by the same author, with particular regard to industrial environmental protection measures:

- Production-integrated environmental protection measures
- Additive environmental protection measures
- Adaption of existing processes (Klingelhöfer 2006, p. 11).

Yet, both classifications do not specifically suit the needs of this work. Hence, a new classification related to those mentioned above will be introduced for this work: environmental investments are defined as investments with the important, yet not necessarily exclusive goal to reduce the environmental impacts of (industrial) business operation. Other goals may be the reduction of energy consumption, the improvement of product quality or the reduction of maintenance expenses. The installation of a new production line with exceptionally high environmental standards, however, is not considered an environmental investment, as its primary goal is the production of goods and not the reduction of environmental impact. A categorization in three types of environmental investments is presented in the following.

3.1.1 Efficiency Investments

The first type of investments, the efficiency investments, usually require the least political intervention. Efficiency investments have an impact on the environment as the consumption of energy or other consumables is reduced by increasing efficiency of the technology. Typical examples are the use of LED technology for lighting or the exchange of old machinery by new ones with higher technical standards and thus higher efficiency. A detailed discussion of efficiency investments is provided in Chiaroni et al. (2017).

These investments have two major effects: by reducing energy and/or material consumption, they reduce the environmental impact and production costs. Therefore, plant operators may have an environmental and economic interest in these investments and a classical cost-effectiveness study can be conducted. From a political point of view, a typical intervention regarding this category of investments is a financial support scheme to promote and accelerate the dissemination of a new or advantageous technology. Due to the inherent economic incentive to invest, the additional publicly funded subsidies may be comparably low but can achieve considerable impact, particularly if a technology is approaching its break-even-point.

On the other hand, efficiency investments may be prone to so-called rebound effects (Bandyopadhyay, 2015). Rebound effects are described as increasing resource consumption that is made possible or caused by an increase in efficiency (Font Vivanco, 2016). For example, due to the reduced energy consumption of LED lighting, more lighting capacity may be installed, without a technical need to do so. Hence, a part of the energy savings is compensated so that the full potential of savings cannot be achieved. This effect, even though not in the focus of this research, should be kept in mind when designing policy instruments for efficiency investments.

3.1.2 Mandatory Investments

Mandatory investments are defined as investments that have no direct economic benefit but are legally enforced, for example by emission limit values. Examples of this type of investments are flue gas treatment installations, but also installations to treat wastewater or other waste in order to reduce its environmental impact. These investments are a special type of investment, as they are directly caused by policy. Nevertheless, other policy instruments may influence them as well. Mandatory investments can have positive economic effects, e.g. regarding publicity and outreach activities. Some processes also generate by-products that can be sold.[5] However, these revenues are by definition expected to be significantly lower than they would have to be in order to meet the economic break-even-point of the investment.

[5] E.g. gypsum is produced in Flue Gas Desulfurization installations to reduce sulfur oxides.

3.1.3 Risk-reducing Investments

The group of risk-reducing investments is considered the most heterogeneous group. It summarizes all sorts of investments that (may) have a positive environmental impact by reducing different types of risks with environmental relation. These may be economic risks for the company, such as increasing prices or fees for fuels, energy or other raw materials. Furthermore, direct environmental risks such as pollution in case of natural disasters or technical failure can be considered. For example, by reducing the amount and criticality of hazardous substances on site, the risk of environmental damage in case of an accident is reduced.

An exemplary investment of this kind is fuel switching, for example from oil to natural gas due to highly uncertain oil prices. Natural gas typically causes lower environmental impacts than oil does. Another example is the switch to less critical substances (e.g. the use of water-based inks for printing instead of solvent-based products), but also the installation of oversized emission reduction installations could be considered. This may reduce the risk of an additional retrofit if decreasing emission limit values are to be expected. Important common characteristics of these investments are the long-term perspective and the irreversibility caused by a large share of sunk costs after installation.

3.2 Investment and Cost Calculation

The aim of the methods to be presented in this chapter is not to calculate the investments and costs of a new installation in every detail but to give an idea about investment and operating costs on pre-study level accuracy, which is for large industrial installations quantified to ± 30% (Chauvel et al. 2003; Geldermann 2014; Peters et al. 2003). While providing realistic cost estimates, the required effort and the amount of data shall be kept at a reasonable level.

3.2.1 Calculation of CAPEX

The term CAPEX (Capital Expenditures) stems from accounting and stands for the fixed assets of a company. Important components are the initial equipment, auxiliary installations, spare parts and related expenditures such as the depreciation of capital equipment. CAPEX are an important item of a company's balance sheet (Hofmann et al. 2012; Large 2009).

Regarding the calculation of CAPEX for emission abatement technologies, various methods exist. According to Chauvel et al. (2003) and Peters et al. (2003) the total capital investment (TCI) is defined as the fixed-capital investment (FCI), which contains the plant and equipment itself, plus the working capital (WC).

The FCI includes the initial investment and the investment for auxiliaries and nonmanufacturing facilities, while the WC accounts for the first fill of raw materials, consumables, etc. that is necessary to operate the installation in the designated manner.[6] Peters et al. (2003) grouped various investment calculation methods according to their general methodology, complexity, and accuracy, as displayed in Figure 3-2. A detailed description of all methods would reach beyond the scope of this work but is provided in Peters et al. (2003). An exemplary application of investment calculation will be presented in chapter 4.

CAPEX is a standard term in accounting and particularly familiar in the Anglophone area, yet not all investment calculation methods are based on this aggregation due to practical reasons. The calculation of some (e.g. operating) cost components may be based on the total investment; therefore, some authors aggregate investment-related costs. This aggregation does usually not fully comply with the definition of CAPEX/OPEX. Exemplary deviations will

[6] A detailed assessment of the working capital is provided in Chauvel et al. (2003, 182-183). In the given context, exemplary components are the first fill of the reagent tanks or the initial catalyst.

be further discussed in chapter 4. Investment calculation approaches based on investment-related costs were published by Rentz (1979), Schultmann et al. (2001), Spengler (1998) and VDI (2001).

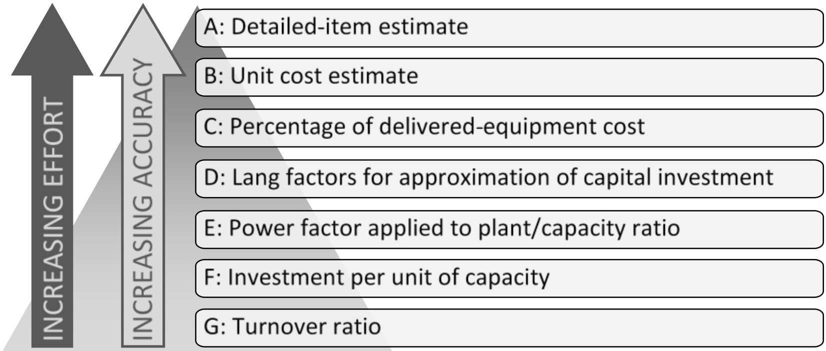

Figure 3-2: Calculation methods for capital investments (Peters et al. 2003).

3.2.2 Calculation of OPEX

OPEX (Operational Expenditures) summarize the ongoing expenditures for running a production plant, business, system or any other industrial entity. In the case of NO_X abatement in LCP, all sorts of consumables, as well as operation and maintenance costs related to the investment, are included (Hofmann et al., 2012). The OPEX of an industrial installation typically consist of fixed and variable operating costs displayed as annual costs (cf. eq. (3-1)).

$$\dot{C}_{op}\left[\frac{€}{a}\right] = \dot{C}_{op,fix}\left[\frac{€}{a}\right] + \dot{C}_{op,var}\left[\frac{€}{a}\right] \tag{3-1}$$

The fixed operating costs $\dot{C}_{op,fix}$ are usually calculated as a percentage of the total investment and account for overhead, insurance, taxes etc. (Peters et al.

2003). The variable operating costs $\dot{C}_{op,var}$ depend on the production output[7] and contain the costs for raw materials, utilities such as electricity and reagents, as well as e.g. waste disposal (Chauvel et al. 2003).

Some cost components such as operation and management expenditures, wages or maintenance cannot be explicitly grouped to one or the other category as they have both, fixed and variable shares (Chauvel et al. 2003). Therefore, they can be separated in further subcomponents, if detailed data is available, or it needs to be decided according to the underlying application, which assignment is more suitable. A detailed exemplary operating cost calculation will also be provided in chapter 4.

3.2.3 Other Cost Components

Apart from the classical cost components mentioned as CAPEX and OPEX, there may be additional expenditures that should be included in an investment calculation. Particularly environmental, social or legal costs are often hidden or voluntary costs. Voluntary costs are not mandatory but may help to improve for example the public image of a plant, such as community relation or environmental projects (Institute of Management Accountants 1996).

It is strongly recommended to screen a project carefully in its early stages in order to identify possible hidden costs and include them in the calculations, even though the expenditures might not occur at the time of investment but sometime later (e.g. plant decommissioning). A list of possible cost components is provided in Table 3-1.

Further important calculation items are contingencies. They are added to a calculation in recognition of the fact that unexpected events or modifications are difficult to avoid in large projects. Usually, such changes of plans come

[7] In the given context, the runtime may be a more suitable base value, as emission abatement installations do not or hardly produce a marketable output.

along with increasing costs. Therefore, contingency factors, typically ranging between 5 % and 15 % of the FCI, are commonly used (Chauvel et al. 2003; Geldermann 2014; Peters et al. 2003).

Moreover, external cost components can be internalized in order to assess the total value of environmental investments. An exemplary study is provided by van der Kamp (2017), complemented by a theoretic discussion in Callan and Thomas (2013). External costs do not have to be paid directly by the plant operator but by the state, the community or other stakeholders. An example is an increasing number of lung diseases caused by air pollution. The treatment has to be paid by the affected people or by the national health care system and is therefore an external cost. However, there might be an indirect internal effect to the company, as for example, the number of sick workers may rise or the revenues may decline due to a negative public image.

External costs can be internalized to get an integrated view of the investment. They are, however, often hard to identify, quantify and monetize and might thus cause a considerable effort with regard to the calculation (Epstein and Rejc Buhovac 2014). A plant operator's interest in considering external costs is often low, as such contemplations are usually not legally enforced. Therefore, due to the focus on the company internal perspective of this work, external costs will not be further investigated in this work (cf. 3.4.3).

Table 3-1: Potential hidden or contingent cost components (Institute of Management Accountants 1996) [R&D: Research and Development].

Potentially Hidden Costs		
Regulatory • Notification • Reporting • Monitoring/testing • Studies/modeling • Remediation • Recordkeeping • Plans • Training • Inspections • Manifesting • Labeling • Preparedness • Protective equipment • Medical surveillance • Environmental insurance • Financial insurance • Pollution control • Spill response • Stormwater management • Waste management • Taxes/fees	**Upfront** • Site studies • Site preparation • Permitting • R&D • Engineering and procurement • Installation **Conventional Company Costs** • Capital equipment • Materials • Labor • Supplies • Utilities • Structures • Salvage value **Back-End** • Closure/decommissioning • Disposal of inventory • Post-closure care • Site survey	**Voluntary** • Community relations/outreach • Monitoring/testing • Training • Audits • Qualifying suppliers • Reports (e.g. annual environmental reports) • Insurance • Planning • Feasibility studies • Remediation • Recycling • Environmental studies • R&D • Habitat and wetland protection • Landscaping • Other environmental projects • Financial support to environmental groups and/or researchers
Contingent Costs		
• Future compliance cost • Penalties/fines • Response to future releases	• Remediation • Property damage • Personal injury damage	• Legal expenses • Natural resource damage • Economic loss damage
Image and Relationship Costs		
• Corporate image • Relationship with customers • Relationship with investors • Relationship with insurers	• Relationship with professional staff • Relationship with workers • Relationship with suppliers • Relationship with lenders	• Relationship with host communities • Relationship with regulators

3.3 Risks and Uncertainties

In scientific literature, various definitions exist for risk and uncertainty in the economic context. According to an early definition of Knight (1921) uncertainty is a risk that is immeasurable and therefore not possible to be calculated. Hubbard (2009, p. 80) proposes a more detailed definition of risk and uncertainty:

- ***"Uncertainty:*** *The lack of complete certainty, that is, the existence of more than one possibility. The 'true' outcome/state/result/value is not known.*
- *<u>Measurement of uncertainty:</u> A set of probabilities assigned to a set of possibilities. Example: 'There is a 60% chance this market will double in five years'*
- ***Risk:*** *A state of uncertainty where some of the possibilities involve a loss, catastrophe, or other undesirable outcome.*
- *<u>Measurement of risk:</u> A set of possibilities each with quantified probabilities and quantified losses. Example: 'There is a 40% chance the proposed oil well will be dry with a loss of $12 million in exploratory drilling costs'."*

In this sense, the measure of uncertainty refers to the probabilities assigned to outcomes only, while the measure of risk contains both probabilities and quantified losses for outcomes.

Bikhchandani et al. (2013) do not distinguish at all between the two terms. They assume that in any case a probability and a loss for an outcome can be assumed, the important question is how good the assumptions are. Other authors use different denominations such as ignorance for what is described above as uncertainty (Schätter 2016).

In the context of this work, the quality of probability distribution assumptions can vary among specific risks but also among different companies/investors. While a specific risk may be rather precisely quantifiable for one investor, it can be very vague for another company operating under different circumstances. Consequently, it is not possible to distinguish precisely between the terms ‘risk’ and ‘uncertainty’ as there are deviations even among different investors. Therefore, both terms are used synonymously within this work.

It is neither possible nor is it the goal to consider all existing risks in this chapter. The following section aims at providing the most relevant risk categories focusing on NO_X abatement in the energy sector. The main aspects of plant-specific identification and evaluation of risks will be further discussed in the sections 3.3.2 and 3.3.3. Risks that endanger the operation of the whole plant, such as earthquakes, volcanos or the like, shall not be considered in this overview, as the plant operator is expected to having them taken into account when building/planning the plant itself (independently of environmental retrofits or sub-investments).

3.3.1 Definitions and Types of Risks

Schätter (2016) provides a detailed overview of different categorizations of risks and uncertainties. For the work at hand, the categorization in aleatory and epistemic uncertainty is considered most suitable and hence introduced briefly in the following.

Aleatory uncertainty describes inherent deviations of the decision situation which affect (amongst others) input data, parameters or model structures (Walker et al. 2003). Exemplary sources of aleatory uncertainty are nature, human behavior including social, economic and cultural dynamics and technical disruptions (Walker et al. 2003). Aleatory uncertainty can hardly be reduced, as research and development are not able to provide comprehensive information (Bertsch 2008; Schätter 2016; Walker et al. 2003).

Epistemic uncertainty refers to the unknowingness with regard to the decision situation. It arises of limited or inaccurate information, measurement errors, imperfect models and subjective judgments (Walker et al. 2003). It is further described as a systematic uncertainty and can hence be eliminated by sufficient study (Senge et al. 2014; Walker et al. 2003). Epistemic uncertainty indicates the amount of uncertainty that could be controlled if the necessary effort is accepted and undertaken (Comes 2011; Schätter 2016).

Four classes of risks (characterized by the source of the risks) based on the publications of International Energy Agency (2014) and International Energy Agency (2007) shall be introduced in the following. This overview focusses on aleatory uncertainty; epistemic uncertainty will be discussed in more detail in the context of the model implementation in chapters 4 and 5.

3.3.1.1 Policy Risks

As the name implies, policy risks are caused by changes in regulation, which affect the operation of the regarded installation. One major policy risk in the given context is an unexpected change in the environmental policy, induced for instance by elections or international influence. Other unexpected changes may be caused by the arrival of new information about climate sensitivity (Fuss et al. 2009), which policy-makers may react to.

Fuss et al. (2009) claim that the risks caused by lacking long-term policy credibility might refrain investors from undertaking necessary investments, so that policy might negatively affect the achievement of its own goals. The impacts of the length of political commitment periods have been investigated in further detail by Buchner (2007).

Apart from a sudden change in environmental C&C policy, there is the politically induced risk of market-based instruments. Particularly emission trading schemes are often complex and difficult to forecast with regard to certificate price developments (European Commission 2013). These market-based risks can be regarded as a sort of continuous risks, compared to the instantaneous risk of a sudden change in policy. If there is a change in policy, stability can be expected afterwards for a certain amount of time (the commitment period). Thus, it might be reasonable for an investor to delay an investment until a possible change (e.g. national elections). The market-based instruments, however, cannot be regarded as stable, because price variations in the past do not necessarily reflect possible developments in the future. Therefore, the impacts of market-based instruments are closely linked to the impacts of economic risks, which will be introduced in 3.3.1.3.

3.3.1.2 Technological Risks

Technological risks primarily influence the CAPEX and OPEX of an investment. Continuous improvement of existing technologies or new technologies may lower the CAPEX. The cost effect of the continuous improvement of technologies can often be monitored in the past, especially for well-established technologies.[8] This positive risk for investors has been investigated by Zhou et al. (2010). New technologies, particularly in the context of emission abatement, usually do not appear from nowhere. A lot of research and development time is necessary before a state of market readiness can be reached. Therefore, plant operators can consider so-called emerging techniques (cf. 2.2.4) in their investment decision-making. Yet, the timing, cost and technical performance of such techniques at market entry are often hard to predict. Elberfeld and Nti (2004) investigated the investment behavior of companies in the context of technology uncertainty in a modeling approach.

Another exemplary technological risk in the given context is the interference of an emission abatement technology with the actual production process and other abatement technologies. Primary measures e.g. reduce the efficiency of a power plant. Secondary NO_X abatement measures, for instance, can raise the content of ammonia in the flue gas, which may cause damage in other flue gas treatment systems or in piping and heating or heat recovery units (European Commission 2006; Rentz et al. 1999).

8 In scientific literature, these aspects are qualitatively and mathematically described by learning and experience curve effects (cf. e.g. Jaber 2011).

Furthermore, technological and political risks may interfere, as policy strongly influences R&D in the pollution abatement sector. This has been analyzed in detail by Krysiak (2011) and Tarui and Polasky (2005). One important effect of political incentives is the so-called 'lock-in effect' (Jaffe et al. 2003). Due to the politically induced public support for one specific technology development path, R&D in this path is enforced whereas it is automatically cut back in other paths due to limited resources – even though the prioritized path might not be the best solution in terms of social welfare (Jaffe et al. 2003).

3.3.1.3 Economic Risks

Economic risks are comparably well known from all kinds of investment decisions. Prices of the investment itself, necessary equipment, fuel or other consumables vary due to various influences such as currency fluctuations, fluctuating demand, political instabilities in delivering countries, etc. Furthermore, the availability of raw materials may be limited, or consumption materials may become scarce in the future. This is particularly critical in the case of long-term investments (Chauvel et al. 2003).

A common way to consider price risks in scientific models are stochastic processes (Birge 2000; Yang and Blyth 2007). A long-term growth rate is assumed, based on either historical data or current forecasts. This trend (or drift) is then overlaid by a random distribution, for example, a Geometric Brownian Motion (Hull 2012). The other risks mentioned above can be integrated into a modeling approach by assuming price jumps or adapting price forecasts (Ross 2011, cf. also 3.5.4). If a detailed modeling of price developments is difficult, sensitivity analyses can be applied as well (cf. 3.4.4).

In the field of risk management, many more than the above-mentioned economic risks have been analyzed across complete supply chains. More details are provided for example in Zsidisin and Ritchie (2008). It is upon the user to select the risks that are of particular relevance for the underlying application. Examples will be provided in the case studies of chapter 6.

3.3.1.4 Legal Risks

Bureaucratic and administrative barriers may be a reason for costly delays in the planning and implementation phase of large investment projects. Documentation and contract risks, as well as jurisdictional risks, are listed as important sources of risk in this category (International Energy Agency 2007).

These risks, however, strongly depend on the situation of a specific plant. The national legislation influences the situation as well as the quality of the enterprise management. Therefore, these risks shall not be investigated in further detail in this work, as it is hardly possible to draw broadly valid conclusions. Nevertheless, these risks may play a major role in actual investment projects. They should hence not be neglected during the risk assessment process.

3.3.1.5 Other Risks

Apart from the four categories mentioned above, there are several more sources of possible risks. Particularly environmental and social risks may be important in the given context and should, therefore, be considered in the early stages of an investment project. Epstein and Rejc Buhovac (2014) provide some more details as well as Bekefi and Epstein (2006) and Hubbard (2009). It is beyond the scope of this work to go into details of all of them; nevertheless, they may be of major relevance for individual projects.

3.3.2 Identification of Risks

The identification of relevant risks for a specific application is an important step during the project-planning phase of industrial investments. As discussed above, not all risks need to be visible at first sight; some of them may be hidden underneath the surface of everyday business.

Therefore, a systematic scanning of all possible risk categories is necessary. Figure 3-3 provides an overview of possible sources of risks. All these sectors should be considered and screened at least briefly, even though one might seem irrelevant for a specific application. Further sectors may be added if experience from other projects or benchmarking investments is available within the company.

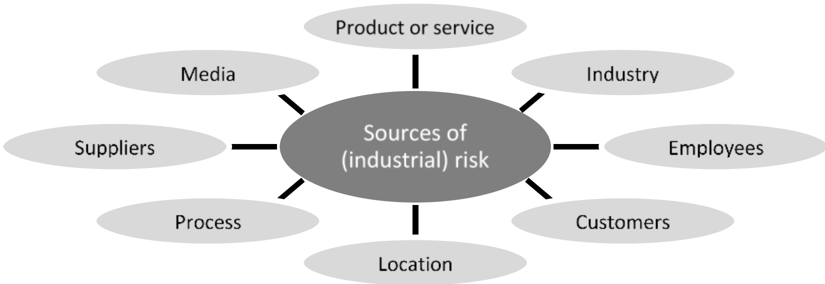

Figure 3-3: Possible sources of risk for industrial environmental investments (cf. Bekefi and Epstein, 2006).

Furthermore, risks can be identified by scanning all considered cost components. Particularly OPEX usually consist of various cost items. Every one of them should be taken into account and analyzed in order to identify possible influencing risks. To give an example, the results of the examination of the cost item 'catalyst cost' might be:

- Only one possible supplier for the catalyst in use.
- Catalyst prices were unstable over the last few years.
- The catalyst contains hazardous materials, which might soon be banned by law.
- etc.

The sole analysis of cost components, however, will not result in a complete picture of risks, as some risks may cause costs that cannot be assigned to an existing cost item. An example is the costs of removing contaminated soil after a reagent tank leakage, which would not be considered at all if the risk of a leakage was not considered.

If existing, the company risk management can provide useful information during the risk identification process. Yet the identification of risks should not be limited to screening the risk management information either. The risks for a specific installation within a plant might be more detailed than the overall considerations of a risk management system and should, therefore, be regarded individually (Hubbard 2009). Further information regarding risk identification is provided in Hubbard (2009), Project Management Institute (2008) and Zsidisin and Ritchie (2008).

3.3.3 Evaluation and Consideration of Risks

To evaluate the identified risks, their possible outcomes and the associated probabilities of occurrence need to be calculated or estimated first. They are primarily depending on the specific application and the corresponding circumstances and can be forecasted based on company internal or external information and experience.

Once the risks, their outcomes, and probabilities are determined, specific risks can be arranged in a portfolio. In risk management literature, the likelihood/consequence portfolio is a widespread tool (Zsidisin and Ritchie 2008). The likelihood of the occurrence of a risk is plotted against the consequences, more precisely against the level of damage caused by the occurrence of the risk, in order to identify the most critical risks.

For the given application, a modified version of this portfolio shall be introduced. It is specifically tailored to investment decisions as it focuses on the monetary outcomes of risks and their influence on the considered cost components. It consists of the two axes ‘influenced share of total costs’ and ‘cost volatility’. Figure 3-4 displays the portfolio, filled with exemplary risks for secondary NO_X abatement.

The influenced share of total costs represents the percentage of the total (annual) costs that may be influenced by the risk. Important cost components are for example the TCI or the catalyst consumption (for SCR). One risk can also influence several cost components. An example is the risk of a lowered ELV, which influences operating costs as well as the TCI.

The cost volatility axis is more complex to scale. Cost volatility can occur as one jump or as a continuous process over a certain period of time. Important is the range that is covered by these fluctuations in relative and absolute contemplation. If the expected range of volatility for an uncertain parameter is not known in advance, historical data or an external benchmarking can be used. To give an example, the cost volatility of permits in the EU might be used as an order of magnitude benchmark value for the rest of the world.[9]

Influenced share of total costs	Cost volatility: low	Cost volatility: high
large	*Moderate influencing of an important cost component* • PR of market-based measures • ER of consumable prices • TR of investment fluctuations	*Major influencing of an important cost component* • PR of threshold cutting • TR of emerging techniques (market entry)
small	*Moderate influencing of a minor cost component* • ER of rising labor costs • ER of insurance cost increase	*Major influencing of a minor cost component* • LR of lawsuit expenses, e.g. in case of permit denial.

Cost volatility

Figure 3-4: Adjusted risk portfolio for long-run investments [PR: Political Risk, TR: Technical Risk, ER: Economic Risk, LR: Legal Risk, major influences are e.g. price jumps or massive cost in-/decreases].

[9] Such an assumption has to be checked for plausibility, as the circumstances in the EU might differ from other regions in the world. This example shall hence not be used without a detailed investigation of the local conditions.

The resulting portfolio can be grouped in three strategic areas. The upper right square contains the most critical risks. For these risks, a detailed investigation is recommended. Intensive research in order to improve the quality of data and forecasts is suitable for risks within this field. The lighter grey squares at the top left and bottom right contain risks, which are either critical in terms of major cost influence or high volatility. It is within the investor's choice how to assess these risks and to decide, whether to investigate them in further detail or not. The risks in the bottom left area are the least critical and can e.g. be transferred into a contingency factor in a pre-study level approach.

To support the portfolio analysis presented above, the German Federal Environmental Agency provides information on environmental damage and the associated costs (Umweltbundesamt 2012). Further investment risks in an uncertain policy environment are quantified in Blyth et al. (2007). Standard risk management literature also delivers more information on the evaluation of risks (cf. e.g. Hubbard 2009; Project Management Institute 2008; Zsidisin and Ritchie 2008). Finally, Surminski (2015) provides insights into the particular aspect of insuring risks with regard to environmental investments in developing countries. This broad overview of risks and risk management shall serve as a basis for the introduction of decision-making methods under risk in the following section. For practical risk management applications, it is certainly necessary to go into more detail, which is, however, not in the scope of this work.

3.4 Investment Appraisal

Investment appraisal methods are generally based on the construction of decision models serving as decision support (Götze 2008; Hundt 2015). Such models simplify and assess the correlations of reality with regard to their principles and impacts (Friedemann 1998). Even if important characteristics of the investment are considered, a majority of the real world processes is not regarded during investment appraisal (Hundt 2015). Therefore, the results of such model-based analyses cannot directly be converted into investment recommendations. Investment calculation cannot replace investment decisions but aims at preparing and supporting them (Kruschwitz 2014).

Figure 3-5 displays an overview of neoclassical investment appraisal methods. The methods considered in this work are marked in dark color, whereas the methods in light color go beyond the scope of this work. The total analysis aims at conducting a complete comparison of different investment alternatives. Hence, (in theory) it considers all investment, funding, sourcing, production, sales and organization decisions of an enterprise with all correlated cash flows. In consequence, the discounting of future cash flows is not necessary for this approach, as all information is supposed to be available (Hundt 2015). In practice, this approach fails due to the complexity and correlations of decisions and the difficulty to forecast uncertain future developments (Schneider 1992).

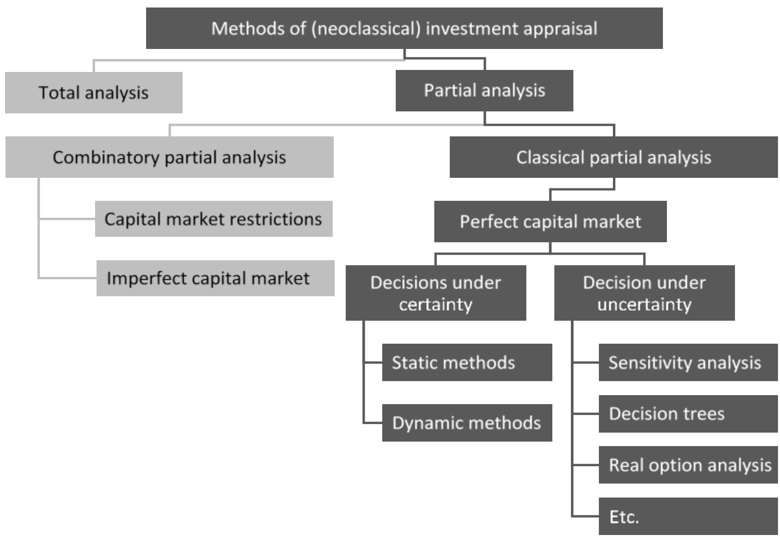

Figure 3-5: Classification of neoclassical investment appraisal methods (cf. Hundt 2015).

A first facilitation of the total analysis is the combinatory partial analyses, but within the scope of this work, they are still too complex. Instead, the classical partial analysis, which does not consider the constant liquidity of the company, is considered suitable for the underlying application (Hundt 2015). This analysis focuses on the question of profitability instead of liquidity. A central assumption and major simplification of classical partial analyses is the perfectly competitive financial market (Perridon et al. 2017).

Furthermore, the methods considered in this work focus on single physical investments (in contrast to investment program appraisal), which are clearly defined and confined regarding their effects (Friedemann 1998). The projects are typically characterized by a long-term perspective and a long-term capital commitment (Götze et al. 2015). The methods to be presented in the following differ with regard to three main aspects:

- the way they transform cash flows of different years/periods
- their target measure(s) (decision criteria)
- their assumptions (Götze et al. 2015).

The resulting profitability decision is based on two main aspects. The criterion of absolute profitability assesses, whether executing an investment is better than rejecting it, whereas the relative profitability criterion investigates, whether investing in project A is more profitable than investing in project B, assuming that A and B are mutually exclusive alternatives (Götze et al. 2015).

This work focusses on relative profitability, as many environmental investments are enforced by law. Therefore, it may be known beforehand that absolute profitability will not be achieved (‘not to invest is not an option’) but the most profitable alternative has to be selected, even though it may still be unprofitable in an absolute economic contemplation.

The aim of the following sections is not to introduce all methods in detail, as there is a selection of textbooks with detailed information available (cf. e.g. Busse von Colbe et al. 2015; Götze et al. 2015; Perridon et al. 2017; Röhrich

2014; Schäfer 2005). Instead, a brief overview shall be provided in order to understand the advantages and weaknesses of the methods with regard to the application at hand.

3.4.1 Static Methods

The static investment appraisal methods are summarized in Table 3-2. They are characterized by their temporal assessment of investments, which is based on average periods. The cash flows throughout the lifetime are annualized so that the costs and revenues of one average period (year) of different investment alternatives can be compared to each other (Busse von Colbe et al. 2015).

Table 3-2: Static investment appraisal methods (cf. Götze et al. 2015; Röhrich 2014).

Name	Decision criterion	Description
Cost comparison	Average annual costs	Revenues are assumed identical among investment alternatives so that the comparison of alternatives is based on costs only.
Profit comparison	Average annual profit	Considers costs, revenues, and the thereof resulting profit of investment alternatives.
Average rate of return	Rate of return in %	Combination of a profit measure with a capital measure. The return is expressed as a rate of interest, the higher the return, the better the rating of the project. It is a relative measure that does not take the absolute size of the projects into account.
Static payback period	Payback time in years	The payback period is the period in which the invested capital is regained from the average surplus of the project. The shorter the payback time, the higher the rating.

While the first three methods in Table 3-2 are strictly committed towards a monetary return or cost aim, the static payback period method calculates the amortization time of an investment (Busse von Colbe et al. 2015). The cost comparison is suitable for investment alternatives with similar or unknown revenues, the profit comparison allows including the revenues in the calculation and the average rate of return aims at selecting the most profitable investment alternative if resources are limited (Perridon et al. 2017).

The calculations of all static methods are comparably intuitive from a methodological point of view (Perridon et al. 2017). Depending on the application, this may not be the case for the gathering of the underlying data. More details and exemplary applications are provided in Busse von Colbe et al. (2015), Götze et al. (2015), Perridon et al. (2017) and Röhrich (2014).

The main criticism with regard to static methods is the ignorance of the temporal course of cash flows. The time value of money is disregarded (Perridon et al. 2017). Furthermore, the focus on an average period may emphasize the first period, as it is directly in sight, even though it might not be representative for the rest of the lifetime (Perridon et al. 2017). Nevertheless, these methods are frequently applied due to their easy implementation and transparent and intuitive results (Busse von Colbe et al. 2015).

3.4.2 Dynamic Methods

The dynamic methods, also called discounted cash flow methods, consider the time value of money (Götze et al. 2015). Therefore, all cash flows need to refer to the same reference time. If the reference time is prior to the time of occurrence of the cash flow, it needs to be discounted, in the opposite case, it needs to be compounded. Eq. (3-2) displays both discounting and compounding, with the net present value (NPV_t) of the net cash flow *NCF* at time *t* (cf. eq. (3-3) with *CIF*: cash inflow; *COF*: cash outflow), the interest rate *r* and the time of occurrence *t* (based on the reference time t_0, *t* is positive for future periods and negative for periods in the past) (Götze et al. 2015).

The net present value *NPV* of an investment project is calculated in eq. (3-4) as the sum of all discounted (or compounded) cash flows that belong to the project, i.e. all cash flows throughout the lifetime of the investment (Röhrich 2014). The resulting *NPV* represents the capital growth of the investing entity caused by the investment (Baecker et al. 2003). Furthermore, the annuity of a project can be calculated as the present value of the investment project equally distributed to the periods (years) of its lifetime *T* (eq. (3-5)). This method is particularly suitable for the comparison of investments with unequal lifetimes (Röhrich 2014).

$$NPV_t = \frac{NCF}{(1+r)^t} \tag{3-2}$$

$$NCF = CIF - COF \tag{3-3}$$

$$NPV = \sum_{t=0}^{T} NCF_t \cdot (1+r)^{-t} \tag{3-4}$$

$$Annuity = NPV.\frac{(1+r)^T \cdot r}{(1+r)^T - 1} \tag{3-5}$$

Table 3-3 summarizes the most common dynamic investment appraisal methods according to Götze et al. (2015) with their investment criterion and a brief description. More detailed information is again provided in standard investment appraisal literature (e.g. Busse von Colbe et al. 2015; Götze et al. 2015; Perridon et al. 2017; Röhrich 2014).

A main difficulty with regard to dynamic investment appraisal methods is the definition of an appropriate interest rate and the precise forecasting of future cash flows (Röhrich 2014). The Institute of Management Accountants (1996) lists further reasons, why dynamic investment appraisal methods are of limited suitability for environmental investments. Important issues named in this reference are the tendency of these methods to favor short-term investments and their lacking ability to consider risks. Due to the consideration of the time value of money, the dynamic methods inevitably place less emphasis on cash flows later in the investment lifetime. Therefore, severe calculation or decision discrepancies may occur in case of long-term investments (Institute of Management Accountants 1996). This issue will be discussed in further detail in chapter 5.

Table 3-3: Dynamic investment appraisal methods (cf. Götze et al. 2015).

Name	Investment criterion	Description
Net present value	Present value of all project-related cash flows	The present value of the gains or losses of an investment is calculated by summing up all past, present and future cash flows of the project discounted or compounded to the considered time t.
Annuity	Annuity	Calculates the annuity of the net present value, which allows for an annualized comparison of investment projects.
Internal rate of return	Rate of return in %	The internal rate of return is the interest rate that leads to an NPV of zero. The higher the return rate, the better the rating of the project.
Dynamic payback period	Payback time in years	The dynamic payback period method is similar to the static one, except for the consideration of the course of time of cash flows. Therefore, all cash flows are discounted according to their time of occurrence and summed up starting from t_0. The payback period or amortization time is the time it takes until the sum of all cash flows becomes positive.

3.4.3 Methods for Environmental Investments

Classical investment appraisal methods have been criticized for several reasons with regard to environmental investments. One main difficulty is that many environmental investments generate no or low revenues. Therefore, investment appraisal methods with solely economic investment criteria rarely promote such investments. Instead, environmental investments are of use for the society and the environment as a whole. In the last decade of the 20th century, several publications dealt with the problem of evaluating environmental investments. An overview of methods and publications is provided by Epstein and Rejc Buhovac (2014), Friedemann (1998) and Institute of Management Accountants (1996).

Most of these methods try to take the whole lifecycle of a product into account and/or internalize external impacts of environmental pollution caused by the products. Therefore, directly product-related costs of stakeholders (such as the government or the society) are internalized by applying cost factors like the ones presented by the German federal environmental agency (Umweltbundesamt 2012). Most common examples of such methods are the Life Cycle Costing (LCC), Full Costing or Activity-Based Costing.

Another comparable approach is the ecosystem service approach that limits the consumption or contamination of natural goods such as water, air or soil, by introducing a tax-like monetary instrument depending on the environmental impact (cf. e.g. Betge 1995; Everard 2017). Schröder and Willeke (1995) recommend a process-oriented contemplation of the whole product beyond company boundaries, comparable to an LCA but with particular regard to the production costs and impacts in different stages of the process. Depending on the type of product and manufacturing technique, there may be company external impacts based on internal investment decisions. Others, such as Schaltegger and Sturm (1994), Lange and Ukena (1996) or Zimmer (2016) recommend multi-criteria decision-making methods that integrate not only monetary but also environmental and social aspects in the decision-making.

Yet, these approaches have no influence on the internal economic reasonability of an investment. Instead, they address investors with diversified motivation, which is not only based on economic aspects. However, incentives for such motivation are scarce and policy measures such as public funding schemes target the 'traditional' economic motivation as well. Therefore, the methods mentioned above will not be further introduced and considered in the following, even though their merits in terms of a comprehensive contemplation shall be acknowledged.

3.4.4 Investment Appraisal under Uncertainty

The methods described above aimed at deterministic investment decisions, i.e. all input parameters were assumed certain. This is a major simplification and falsification of real-world problems, as future-related input data can hardly ever be considered certain (Perridon et al. 2017). Therefore, Table 3-4 displays a selection of appraisal methods under uncertainty.

These methods are mostly extensions of the methods under certainty. To give an example, the NPV method is often used for evaluating uncertain investments. The results under certainty form the basis, which is then further investigated according to one of the methods described below (Perridon et al. 2017). Hence, the decision criterion is not mentioned in Table 3-4, as it depends on the original investment appraisal method to be used.

A method that is not mentioned separately in the table above is the scenario analysis. This method can be applied in combination with all above-mentioned methods and is commonly used to reduce the complexity of the decision-making. Instead of calculating a large number of incremental steps of different input values, scenarios can be defined by the decision-makers and investigated according to the selected appraisal method (Busse von Colbe et al. 2015). This approach allows including the expertise of decision-makers and forecasts. Yet, it may also limit the validity of the results, as the defined scenarios may not suit the actual future development (Schätter 2016). More details regarding the scenario analysis are provided in Hassani (2016) and Schätter (2016).

Table 3-4: Appraisal methods for investments under uncertainty (cf. Götze et al. 2015).

Name	Description
Risk-adjusted analysis	The input data for investment appraisal methods is adjusted in order to account for the risk involved. A typical example is the use of a risk-adjusted interest rate, but risky cash flows or the economic life can be adopted as well.
Sensitivity analysis	It investigates how much the target value changes when input parameters vary, or which critical input thresholds need to be reached in order to achieve a certain target value. Furthermore, the robustness of the results can be tested.
Risk analysis	The risk analysis assumes probability distributions for uncertain inputs. Taking the interdependencies between input and target measures into account, a probability distribution of possible values of a target measure can be derived.
Decision-tree method	Dynamic, model-based approach that investigates series of decisions in a scenario based environment. It may incorporate the gain of new information in between the subsequent decision times. Will be explained in more detail in section 3.5.3.2.
Option pricing models	Will be discussed in detail in section 3.5.

A further way to investigate possible future developments is the use of stochastic processes, evaluated for example by a Monte-Carlo-Simulation. This approach is particularly suitable for continuously developing parameters such as prices that are commonly considered in risk analyses and option pricing models and will be introduced and discussed in section 3.5.4.

Due to its relevance for the work at hand, the risk-adjusted analysis (with particular regard to the risk-adjusted interest rate) and the sensitivity analysis will be briefly introduced in the following. More information on all mentioned appraisal methods is provided in e.g. Baecker et al. (2003), Busse von Colbe et al. (2015), Hering (2008), Perridon et al. (2017) and Röhrich (2014).

The sensitivity analysis tests the robustness of a solution. Selected input values are intentionally varied in order to analyze their influence on the results. It hence examines the extent to which certain parameters (model coefficients) can be changed without affecting the decision (Perridon et al. 2017). This method is particularly suited to investigating non-stochastic input parameters (such as the TCI, the depreciation time, the interest rate, etc.) or to find boundary values for stochastic inputs such as commodity prices (Götze et al. 2015). The method is rather easy to handle, its main criticism is the missing consideration of interdependencies between variables (Baecker et al. 2003; Götze et al. 2015).

The risk-adjusted interest rate can be applied for dynamic appraisal methods only. A risk bonus is added to the risk-free interest rate in order to account for the project risks (Perridon et al. 2017). It is very difficult to determine the risk-adjusted discount rate properly. One alternative for all tradeable assets is the Capital Asset Pricing Model (CAPM), which was developed for financial assets and is explained in detail in finance literature (cf. Hull 2012; Krug 2015). In practice, the risk-adjusted discount rate is often not more than a good guess of the decision-makers or a standard value for the whole enterprise or sector that is not adapted to the specifics of the considered investment decision (Peters et al. 2003). Due to these difficulties, the Institute of Management Accountants (1996) recommends for environmental investments to make adjustments to the cost and benefit profiles rather than to the discount rate, as they apply independently of the time value of money and they are easier to be estimated at satisfying accuracy.

A further characteristic of uncertain investment decisions is that there may be differing decision recommendations depending on the assumed state of input parameters. While a best-case scenario might recommend investment alternative A, the base-case or worst-case scenario (or any other investigated scenario) might recommend different investment alternatives. In these cases, decision theory provides several alternative decision-making rules, two popular examples are the Maximin- or the Hurwicz-rule (Umweltbundesamt 2012). The selection depends on the characteristics of the investment and on the risk preference of the decision-maker. Furthermore, utility functions of the decision-maker can be assumed (Busse von Colbe et al. 2015; Bikhchandani et al. 2013). More details and a full list of decision rules are provided in e.g. Bamberg et al. (2012), Bikhchandani et al. (2013), Götze et al. (2015) and Laux et al. (2014).

Finally, the investment appraisal method that is appropriate for the application needs to be selected according to the risks and uncertainties to be considered and the relevant circumstances. Relevant circumstances are not only external influences but also company specific experience, guidelines and culture. The more complex methods are generally expected to deliver increasingly detailed results. Yet it should be favored to use a method that can be handled properly, rather than completely ignoring risks and uncertainties if the complexity of other methods overburdens the decision-maker(s).

3.5 Real Option Analysis (ROA)

ROA goes back to Black and Scholes (1973) and was pioneered by Myers (1977) before being broadly discussed and applied to investment projects over the last decades. Lee (2011, p. 4445) summarizes the basic idea of ROA, stating that "*a firm that decides to make an irreversible investment exercises an option. The lost option value is an opportunity cost that must be incorporated in the assessment of the investment cost, i.e. an essential feature in explaining the lack of consistency between neoclassical investment theory and* *investment behavior.*" ROA can incorporate managerial flexibility with regard to several types of options, an overview is provided in section 3.5.1 and by Brach (2003), Lee (2011), and Trigeorgis (1996). Three common characteristics of financial and real options are the irreversibility of the decision when executing the option, the flexibility of execution[10] and the uncertainty about the future development of value-determining parameters (Hundt 2015). According to Hommel and Pritsch (1999), ROA is particularly recommended in applications with high managerial flexibility and high overall risk.

The ROA approach came up because classical investment appraisal methods have been criticized for several reasons. Sarkis and Tamarkin (2005, p. 290) state that "*every project that may be delayed competes with itself at future dates"*. Traditional investment appraisal methods usually consider either reversible or now-or-never decisions (Dixit and Pindyck 1994). Especially regarding irreversible investments, this is a major simplification that does not account for the actual situation of an investor (Zhou et al. 2010). Several more issues have been criticized accordingly. A further discussion of difficulties and failures of NPV-based decision-making, particularly related to the estimation of risk-adjusted interest rates, is provided by Hull (2012, pp. 765–766).

In general, ROA is characterized by the determination of a real option value, which is an opportunity cost item subtracted from the NPV of an investment when exercising the option (Dixit and Pindyck 1994).[11] The real option value accounts for the value of managerial flexibility with regard to irreversible options. Furthermore, the real option value incorporates the valuation of risks and uncertainties. Therefore, the risk-free interest rate can be used for the determination of the NPV, which is significantly easier to determine than the risk-adjusted interest rate (Brach 2003).

[10] An option gives its holder the right, but no obligation to execute it (i.e. to take an action at a predefined cost) in the future (Trigeorgis and Reuer 2017).

[11] By exercising the option, the real option value is lost due to the irreversible character of the option. Once exercised, the option is no longer available in the future; hence, its value is lost.

In the following section, the basics of ROA, existing types of options, option valuation methods and relevant stochastic processes will be introduced with particular regard to the application in this work.

3.5.1 Basics and Definitions

In order to understand and apply ROA, a brief introduction to (financial) option theory is necessary. Financial options can be classified in call and put options and in American and European options. A call option allows the holder to buy an asset at a certain date or within a certain period for a certain price, while a put option allows selling an asset at a certain date or within a certain period for a certain price (Uszczapowski 2008; Hull 2012).

American options can be executed at any time between the starting and the expiration date, European options can only be exercised on the expiration date (Hull 2012). Furthermore, options *“are referred to as in the money, at the money, or out of the money. If S is the stock price and K is the strike price*[12]*, a call option is in the money when S > K, at the money when S = K, and out of the money when S < K. A put option is in the money when S < K, at the money when S = K, and out of the money when S > K. Clearly, an option will be exercised only when it is in the money. In the absence of transactions costs, an in-the-money option will always be exercised on the expiration date if it has not been exercised previously.”* (Hull 2012, p. 201)

These definitions can be applied accordingly for real options and will be referred to in the following. Beyond call and put and European and American options, there are several more subcategories and exotic options mentioned in financial literature (cf. e.g. Rieger 2016). In the scope of this work, however, this standard categorization appears sufficient.

12 The strike price is the price noted in an option contract that has to be paid for the underlying asset when exercising the option (cf. Hull 2012, p. 7).

Many real option problems have been developed and solved over time. Several examples are provided by Dixit and Pindyck (1994). The so-called basic real option model investigates a project with a value *PV* following a Geometric Brownian Motion. The two main questions are, whether the firm should invest in a project and if yes, when. The resulting mathematical problem is an optimal stopping problem, which can be solved continuously by a dynamic programming approach considering Itô's Lemma and the smooth pasting and value matching conditions (Dixit and Pindyck 1994).

From a mathematical point of view, the continuous solution of real option problems is comparably difficult, as it involves partial differential equations and other complex mathematical methods (Peters 2016). With increasing complexity of the application, it may not even be possible to solve the partial differential equation(s) analytically. This is one of the major drawbacks of its practical relevance, as investigated by Ampofo (2017) and He (2007).

Simplifications are possible by discretizing decisions and/or by the use of numerical approaches. For the application at hand, a further simplification can be achieved as the question of whether to invest can often be answered by regulation.[13] Therefore, the focus is on the question of when to invest, which reduces the complexity as no decision threshold has to be defined. Further discussions will be provided in the following sections as well as in the model description in chapter 5.

[13] As policy instruments can enforce investments, the question is no longer if, but when to invest. This aspect will be discussed in more detail in 3.6.

3.5.2 Types of Options

Real option literature agrees on several types of options. The precise delimitation, however, varies among different authors. Peters (2016) defines three simple types of options, the so-called common options:

- Option to defer
- Option to expand or contract
- Option to abandon (or switch).

Other options, such as compound, growth, barrier or rainbow options, are variations or combinations of simple options, i.e. they are options on options (Peters 2016). With regard to the focus of this work, it is considered sufficient to explain and understand the three simple options, as they are the basis for all other types of options. Further details about more complex options are provided for example by Smit and Trigeorgis (2012). A short description of the three simple options is provided below.

3.5.2.1 Option to defer

The option to defer is one of the most important options for investment decision-makers (Hull 2012). As the name implies, it consists of the option to delay a project, if uncertainty about future developments overarches a certain level. The idea of this option is that by waiting a certain period of time, uncertainty about future developments of relevant parameters may be resolved (or reduced) so that a more elaborated decision can be made (Dixit and Pindyck 1994). The option represents an American call option on the value of the project (Brach 2003; Hull 2012; Peters 2016).[14]

[14] In certain applications, it may also be a European option, if there is only one reasonable point in time in the future to make the decision. In most cases, however, American options are more suitable for industrial applications.

3.5.2.2 Option to expand or contract

The option to expand *"is the option to make further investments and increase the output if conditions are favorable. It is an American call option on the value of additional capacity. The strike price of the call option is the cost of creating this additional capacity discounted to the time of option exercise. The strike price often depends on the initial investment. If management initially choose to build capacity in excess of the expected level of output, the strike price can be relatively small."* (Hull 2012, p. 771)

The option to expand is a typical example of the relevance of real option thinking in the context of industrial decision-making. Real option thinking (described in more detail in section 3.5.5) describes the deliberate consideration of options during decision-making (Menon and Varadarajan 1992). Hence, decision-makers actively incorporate the gained or lost value of creating or destroying options with regard to future decisions in their current decision (Leslie and Michaels 1997). One example of this kind is the preparation of auxiliary equipment for a later addition of capacity. In this case, a future additional installation can be directly integrated into the existing infrastructure, which may save a significant amount of costs at a later stage, while the initial surplus for a higher capacity of the auxiliary equipment may be a lot lower.

The option to contract is the contrary, i.e. the option to reduce operation at a later stage. Therefore, it is an American put option on the value of the lost capacity (Peters 2016). Its strike price is the present value of the future expenditures saved (Hull 2012).

3.5.2.3 Option to abandon (or switch)

The option to abandon is an American put option on the project's value, which incurs the option to sell or close down a project. The strike price is the liquidation value less any closing-down costs. If the liquidation value is low, the strike price can be negative (Hull 2012).

More likely than the sole abandonment of a project is to switch the resources from one project to another project. Typically, a firm abandons the original project and starts a new project at the same time (Peters 2016). The option to switch is thus a more complex option because a decision has to be taken between two interdependent projects, both involving uncertainty. It can thus be considered as an option that consists of two incremental options (Peters 2016).

3.5.3 Option Valuation

Several real option valuation methods have been published over the last decades, starting with the work of Black and Scholes (1973), which introduces the so-called Black-Scholes equation. However, not only Brach (2003, p. 9) criticizes this approach by stating that *"the Black Scholes formula, which is used to price financial options, may indeed not be the right formula to price many real options. Several of the basic assumptions and constraints that come along with the Black Scholes equation simply do not hold in the real word (…). This, however, does not imply that the use of real options analysis is impractical or incorrect. There are other methods to price real options that can be applied."*

In order to select an appropriate option valuation method for the given application, it is important to understand the basics of real option pricing methods. Baecker et al. (2003) provide an overview of methods to valuate options (Figure 3-6). In the following, the approaches that are considered the most relevant for the type of applications at hand will be introduced briefly. For further understanding and implementation of the most common approaches Brach (2003), Hull (2012), Kodukula and Papudesu (2006) and Peters (2016) provide descriptive explanations and examples.

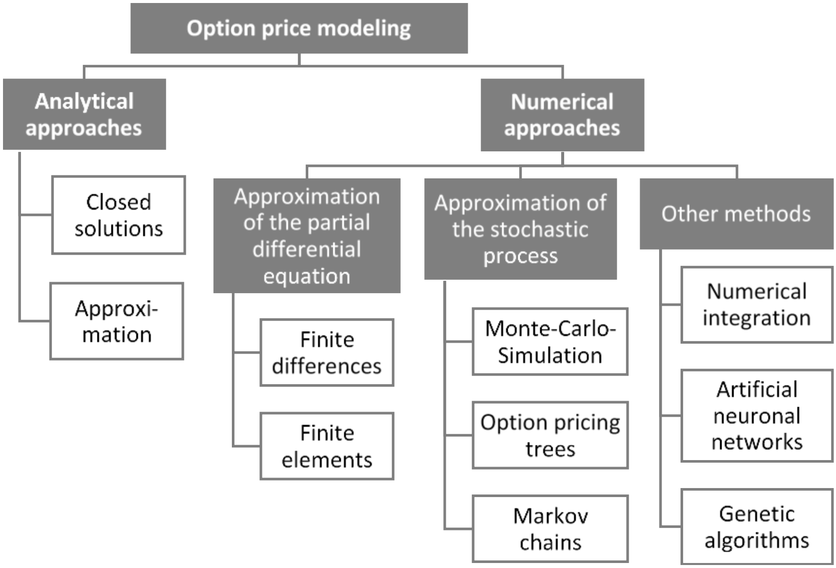

Figure 3-6: Option pricing methods (Baecker et al. 2003).

3.5.3.1 Analytic Approaches

In the history of option valuation, a variety of analytic solutions for real option problems has been published (cf. Brach 2003). The most common analytic approach, particularly used for financial option valuation, is the Black-Scholes equation and modifications or approximations thereof.

Black and Scholes (1973) developed a partial differential equation (PDE) that offers a closed-form solution for dividend-free European call options based on a continuous time stochastic process (Geometric Brownian Motion). The idea of the Black-Scholes equation is to valuate options based on only five parameters. The PDE can be noted as displayed in equation (3-6)

$$\frac{\partial OP}{\partial t} + rS\frac{\partial OP}{\partial S} + \frac{1}{2}\sigma^2 S^2 \frac{\partial^2 OP}{\partial S^2} = rOP \qquad (3\text{-}6)$$

with the parameters:

$OP =$ price of a call option or other derivative contingent on S
$S =$ stock price
$t =$ time between 0 and T (maturity date)
$r =$ risk-free interest rate
$\sigma =$ price volatility of the underlying stock (Hull 2012).

The PDE can also be adapted to other types of options or stochastic processes, yet the resulting PDE might require a numeric solution. More details about the PDE, possible solutions and necessary assumptions are provided in Hull (2012). This approach is comparably easy to use due to the closed-form solution. However, it lacks transparency regarding the influence of individual parameters, assumptions and boundary conditions (Uszczapowski 2008). It is suitable for low-dimensional problems, which means in contrary that solutions for multi-dimensional problems (like many industrial investment decisions) are difficult to achieve (Longstaff and Schwartz 2001; Stentoft 2004).

For applications that cannot be solved analytically, it may be possible to derive closed-form solutions for approximations of the original problem. To give an example, two or more correlated variables could be integrated into one variable in order to reduce the dimensions of the problem. Depending on the type of problem and the required accuracy of the results, such approximations might still deliver acceptable results, especially in case of order of magnitude studies. The advantage of this approach is its simplicity, whereas the impact of simplifications might falsify the results and disguise the influence of specific parameters (Baecker et al. 2003).

3.5.3.2 Numerical approaches

The scheme in Figure 3-6 classified the numeric option valuation approaches in three subcategories. In the following, a short introduction to all of them will be provided, with an emphasis on the approximation of stochastic processes, which is considered most relevant for the given type of application.

3.5.3.2.1 Approximation of the PDE

In order to avoid the difficulties of solving a PDE, the discrete equivalent of the PDE can be used for option valuation (Baecker et al. 2003). Possible methods to solve the resulting problem are the finite differences and finite element methods.

Such approaches are frequently used in the fields of engineering and natural sciences. In economics and finance, there are scientific discussions (Trigeorgis 1996), but applications in the field of real options are comparably scarce (Baecker et al. 2003). Especially for multidimensional problems, the complexity is very difficult to handle (Hommel and Lehmann 2001; Baecker et al. 2003).

3.5.3.2.2 Approximation of the stochastic process

As discussed above, a common characteristic of real option applications is the existence of at least one uncertain parameter. This/these parameter(s) is/are often assumed to follow a stochastic process. Depending on the type of parameter, different processes are more or less suitable (cf. 3.5.4).

A brief introduction of frequently used methods for different types of processes is provided below. Important characteristics of the stochastic processes are (amongst others) the range of possible states of the investigated parameter, continuous or discrete contemplation and interdependencies between past and future developments (e.g. Markov property).

3.5.3.2.3 Option Pricing Trees (Binomial Pricing Model)

The basic (i.e. binomial) option pricing tree is based on the binomial pricing model of Cox et al. (1979). Its idea is not to use a PDE or estimates of volatility but probability distributions of state variables to evaluate future developments. In the easiest (the binomial) case, there are only two possible states of the asset value, an upper and a lower one (cf. Figure 3-7). Equation (3-7) displays the value of the asset *S* in t_1 with the path probability *q*, the factor for 'path up' *u* and the factor for 'path down' *d* (Brach 2003; Hull 2012).

$$S_1 = \frac{[q \cdot uS_0 + (1-q) \cdot dS_0]}{(1+r)^t} \qquad (3\text{-}7)$$

By setting up a riskless portfolio, also called levered hedge [15], Cox et al. (1979) derived a formula for pricing financial options. As long as the characteristics and assumptions of real options follow the same rules, this formula can also be used for real options. A detailed introduction is provided in several publications, cf. Brach (2003), Hull (2012), Kodukula and Papudesu (2006) and Peters (2016).

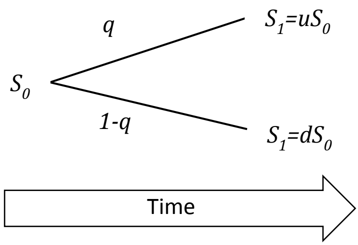

Figure 3-7: Schematic example of a pricing tree branch (cf. Hull 2012).

[15] A levered hedge or riskless portfolio is a portfolio of assets that achieves the same outcome at the end of its life, no matter which way the price of the share moves. A detailed explanation is provided in Hull (2012, p. 254) and Peters (2016, p. 36).

Pricing trees are based on a discrete time scheme which suits the needs of most industrial investment decisions. Multidimensional problems are difficult to implement as the calculation effort increases exponentially with the number of nodes and branches to be considered (Hull 2012). The difficult prediction of future states and probability distributions is another disadvantage of this method. However, there is a comparably large number of studies for real option applications based on this approach (Lee and Shih 2010; cf. e.g. Hundt 2015; Xu et al. 2013), so that its practical relevance is certainly not to be denied. A detailed discussion of the method and its applications is provided by Brach (2003) and Kodukula and Papudesu (2006).

3.5.3.2.4 Monte-Carlo-Simulation

The idea of Monte-Carlo-Simulation is to model and assess a large number of exemplary paths following the rules of the underlying stochastic process. The mean of the results of all paths (no matter if it is the NPV in case of standard investment appraisal or the real option value in case of ROA) can be regarded as the risk-neutral expected value (Baecker et al. 2003).

Monte-Carlo-Simulation is a flexible tool that can be adapted to the specific needs of the application, examples are provided by Laurikka and Koljonen (2006) and Muche (2007). Especially in case of real option applications with characteristics that do not (fully) comply with standard financial option features, it is possible to adopt the simulation to the specific needs. In the case of American options, however, the use of a standard Monte-Carlo-Simulation is more difficult, as early exercise opportunities cannot be assessed directly (Hull 2012). One possibility for such applications is to discretize American options and regard them as a series of European options that can be handled with a dynamic programming approach (cf. 3.5.4.4). Moreover, a modification of standard Monte-Carlo-Simulation has been developed specifically for American option valuation: the Least Squares Monte-Carlo-Simulation.

3.5.3.2.5 Least Squares Monte-Carlo-Simulation (LSM)

The LSM approach, published by Longstaff and Schwartz (2001) and discussed by Stentoft (2004) is an approach specifically suited to multidimensional American option applications. Its aim is to approximate the value of American options by simulation, keeping the computational effort low in relation to the complexity of the problem, while still achieving high-quality results. The basic idea is to "*regress the ex post realized payoffs from continuation on functions of the values of the state variables.*" (Longstaff and Schwartz 2001, p. 114)

Various types of stochastic processes, such as Geometric Brownian Motions, but also jump diffusions or other more exotic processes can be handled by LSM. Yet, in the case of multidimensional problems, the considered factors need to correlate to a certain extent. Otherwise, a least-squares regression will not deliver reasonable results (Longstaff and Schwartz 2001). Exemplary applications in the energy sector were published by Boomsma et al. (2012) and Zhu and Fan (2011).

Further modifications and advancements of Monte-Carlo-Simulation, such as the Exercise Boundary Parameterization Approach (EBP) shall be mentioned here for the sake of completeness (cf. Hull 2012). Yet, such approaches are not considered relevant for the given application and shall hence not be introduced in more detail.

3.5.3.3 Others

Regarding the methods summarized as 'others' in Figure 3-6, the artificial neural network approach is of particular interest in the real options community. It is designed for a large set of input data compared to a significantly lower amount of output data or state variables.

Taudes et al. (1998) provide an illustrative example of a company that wants to decide which product to produce in order to maximize the output. Based on various input parameters, the self-learning network teaches itself, which variables are most important and which thresholds they need to reach in order to adapt the strategy. Hahn (2013) and Taudes et al. (1998) provide more detailed information about the mathematical implementation of such a network.

The most important disadvantage of this approach is the large amount of data that is needed to set up and calibrate the network (Yang et al. 2017). In an industrial context, if data is available, it is usually historic data so that the approach assumes a forward projection not only of stochastic data (as other stochastic approaches do as well) but also of the influence and relevance of specific parameters in the past. Depending on the context of the application, this does not necessarily suit the actual situation. Furthermore, the determination of the major influencing factors usually happens in a black box environment. Without detailed knowledge of the methodology itself and the underlying data, it will be hardly possible for managers or investors to understand the drivers and mechanisms of the evaluation process (cf. Mostafa et al. 2017).

Genetic algorithms and numeric integration face the same difficulties. Without going into detail, genetic algorithms are an alternative to the recursive Bellman optimization[16] for optimization applications. However, the lacking transparency and the complexity of the underlying problem do not support the use of such an approach in the context of this work (cf. Yang et al. 2017). Furthermore, unlike in the financial sector, most industrial real option applications do not require the high level of detail and accuracy these models can achieve but focus on the general understanding and consideration of the value of options (cf. Yang et al. 2017).

A brief literature survey identified some studies and exemplary applications of these 'other' methodologies in the field of real options, yet most works focus on highly detailed option pricing models rather than on practice-

[16] Also called dynamic programming, cf. 3.5.4.4.

oriented comprehensible applications.[17] This leads to the assumption that the disadvantages mentioned above (particularly the complexity of the methods and the huge amount of data required) dominate the advantages for the type of applications regarded in the work at hand.

3.5.3.4 Comparison

Table 3-5: Characteristics of the most suitable option valuation methods.

	Black-Scholes equation	Option pricing trees	Monte-Carlo-Simulation	LSM
Focus type of options	European	Primarily European		American
Time scheme	Continuous	Discrete		
Multi-dimen-sionality	Hardly possible	Computation-ally limited	Possible, but dependencies may blur	Possible, if variables correlate
Quality of results	Analytic solution	Depending on the quality of in-put/forecasting data and applica-bility of the method (according to the predefined assumptions)		Depending on qual-ity of input data. Degree of input parameter correla-tion determines quality of the regression.
Complexity/ computa-tional effort	Low, if parameters are available	Exponentially increasing with number of branches	Comparably low, depending on the stochastic process and the number of runs	Higher than MCS due to regression, but still manageable for many applica-tions
Trans-parency	Black-box, non-transpar-ent influences (e.g. volatility, drift)	Illustrative if number and type of alterna-tives is clear	'Easy' to understand, frequently used	More complex but still 'easy' to under-stand. Interdepend-encies between influencing parame-ters may be ignored

[17] Important publications in this field are summarized by Baecker et al. (2003, p. 30), Mostafa and Dillon (2008) and more recently by Yang et al. (2017).

Table 3-5 provides an overview of the option pricing methods that are considered most relevant for the regarded application. It reveals major methodological deviations between the analytic Black-Scholes equation and the numeric approaches. LSM is mentioned individually due to its specific characteristics, even though it is an extension of standard Monte-Carlo-Simulation.

3.5.4 Stochastic Processes and Dynamic Programming

Stochastic processes are fundamental to the use and implementation of most option valuation techniques. Therefore, a brief introduction, with a particular focus on the processes considered relevant for the application at hand is provided below. Furthermore, the dynamic programming approach as an optimization technique will be used for the implementation in chapter 5 and shall hence be introduced here.

3.5.4.1 Geometric Brownian Motion (GBM)

The most frequently used stochastic process for real option applications is the Geometric Brownian Motion.[18] Its idea is that in a small period of time, the development of the underlying parameter is normally distributed and the developments in two non-overlapping periods are independent (Hull 2012). The value of the uncertain parameter at a future time has a lognormal distribution (Hull 2012). Detailed descriptions about the GBM are provided in various publications. The following description is based on Ammann (2001), Hull (2012), Petters and Dong (2016) and Ross (2011). A stochastic process S_t is called a Geometric Brownian Motion (GBM) with drift μ and volatility σ if it is a solution of the stochastic differential equation in (3-8) where μ and $\sigma > 0$ are constant and ΔW is defined as a Wiener process, and ϵ is a normally distributed random number (cf. eq. (3-9)).

[18] The GBM and its assumptions are e.g. used for the Black–Scholes model (Hull 2012).

$$dS_t = S_t \mu dt + S_t \sigma dW \tag{3-8}$$

$$\Delta W = \epsilon\sqrt{\Delta t} = \sqrt{\Delta t}\,\mathcal{N}(0,1) \tag{3-9}$$

For a further discussion of the GBM in continuous time shall be referred to the already mentioned literature. As the model implementation in this work is based on discrete time steps, a discrete approximation of the continuous process can be used for price path simulations. Ammann (2001) and Xu et al. (2013) mention the approximation in eq. (3-10) whereas (Hull 2012) uses the approximation in eq. (3-11). The expected mean of the process is calculated in eq. (3-12).

$$S_t = S_0 + \Delta S = S_0 e^{\left(\mu - \frac{1}{2}\sigma^2\right)t + \sigma\epsilon\sqrt{\Delta t}} \tag{3-10}$$

$$\Delta S = \mu S_0 \Delta t + \sigma S_0 \epsilon \sqrt{\Delta t} \tag{3-11}$$

$$\mathbb{E}[S_t] = S_0 e^{\mu t} \tag{3-12}$$

The discrete time simulation of a price path following GBM is based on the random walk approach (Petters and Dong 2016). For every considered time step t the value is statistically determined according to equation (3-10) or (3-11). The value of the next period hence only depends on the value of the current period, without considering the previous step. Therefore this process is said to have 'no memory' as it is not influenced by its past development but only by its current state, the random distribution of ΔW and the drift and volatility constants. It thus follows the strong Markov property, which may seem counterintuitive for price developments and can be a major simplification for many applications (Peters 2016). Furthermore, GBM is a non-negative process, i.e. it will never reach or drop below zero, which suits the characteristics of the price paths for most industrial commodities (Ross 2011).

The applicability of GBM for economic developments of various kinds has been investigated by Marathe and Ryan (2005). They conclude that some historical developments did follow the rules of a GBM yet others did not. Its applicability is thus questionable yet there is no perfect process model suiting all kinds of developments. To a certain extent, GBM can be applied for price paths, at least in early planning stages. However, it should not solely be relied on this approach without questioning its assumptions and simplifications, particularly when investigating newly introduced processes or disruptive future developments.

3.5.4.2 Mean-Reverting Processes

Mean-reverting processes are frequently used for modeling commodity prices in financial applications.[19] The main idea is that on the long-run, the price of a commodity is linked to its long-run marginal costs. This effect is only reflected by mean-reverting processes but not by GBM (Ewald and Yang 2008).

A broad variety of such processes has been introduced in the past. One famous example is the so-called Geometric Ornstein-Uhlenbeck process, used by Dixit and Pindyck (1994) for pricing real options, as displayed in eq. (3-13). Equation (3-14) represents a discrete time approximation of the continuous process, which was applied in e.g. Campbell (2013) and Insley and Rollins (2005). c is the price of the considered commodity, $\bar{c}$ the long-run price average, β the mean reversion parameter, σ the volatility and dW an increment of a Wiener process. ϵ is a normal distribution with the parameters $\mathcal{N}(0,1)$.

$$dS = \beta(\bar{S} - S)dt + \sigma S dW \tag{3-13}$$

$$S_t - S_{t-1} = \beta\Delta t(\bar{S} - S_{t-1})dt + \sigma S_{t-1}\sqrt{\Delta t} \cdot \epsilon_t \tag{3-14}$$

19 Lutz (2010) provides a broad overview of exemplary applications and more detailed explanations.

This mean-reverting process is a special case of a general Itô process. It does not consider a drift parameter, as the long-run price is expected to be a constant value (Insley and Rollins 2005). It will be discussed in section 3.6.2, why this type of processes is not of particular interest for the application at hand.

Mean-reverting processes with drift exist as well, are, however, mathematically more complex and therefore not regarded in further detail in this work. Particularly the contemplation of only a few (usually less than 10) decision times, opposes the use of such computationally complex processes and limits their advantages in contrast to GBM.

3.5.4.3 Jump Processes

Prices or other expenses do not necessarily follow continuous processes such as the GBM or mean-reverting processes. They may also jump in case of disruptive events. A reason for such jumps can be policy measures. Tolls or taxes, as well as other monetary policy instruments, may cause price jumps when they come into force. Such jumps can occur in both directions, i.e. prices and costs can increase or decrease (e.g. caused by funding schemes) but again, they are usually not expected to drop below zero.

One way to implement jumps mathematically are the so-called jump-diffusion processes, which combine a continuous price process with jump events. They were first introduced by Merton (1976) and are explained in detail by e.g. Kou (2002). Yet for the application at hand it is considered sufficient to simulate possible jumps as Markov jumps and combine them directly (by summing up the values of both processes) with the stochastic price paths.[20] The details of the implementation will be explained in chapter 5. This approach is more intuitive and can easily be adapted to the assumptions of specific scenarios.[21]

[20] Due to the comparably small number of decision times, a large number of Monte-Carlo paths can be calculated, which increases the quality and reproducibility of the results.

[21] E.g. jumps can be allowed in every or only in predefined periods, the number of jumps can be limited, the value of future states (i.e. the height of the jumps) can be randomized, etc.

Markov jumps are defined as jumps that follow the strong Markov property, i.e. they only depend on the current state of the considered variable and the transition probability matrix, independently of the history of the process (Ibe 2013).

An exemplary transition matrix is displayed in Table 3-6. In this case, if the variable is in state A at time t_0, the probability that it will stay in A in t_1 is 0.9 and the probability for a shift to B is 0.1. If the process is once in state B, it will never jump back, as the probability for a shift from B to A is 0. This example hence displays a single shifting option, which could be the case for a cut back of an investment support scheme. Once it has been eliminated, there is 'no way back' considered. By modifying the numbers, a shift back can be allowed as well.

Table 3-6: Transition Matrix with exemplary probabilities for the application at hand.

	A	B
A	0.9	0.1
B	0	1

If the jump times are discrete, the process is also called a Markov chain, which is the most relevant case for the application in this work (Ibe 2013). Furthermore, a finite number of jumps in a finite interval are considered in the application at hand. The process can hence be called a pure jump process, in contrast to an explosive process with an infinite number of jumps in a finite interval (Ibe 2013).

3.5.4.4 Dynamic Programming

Dynamic programming, also known as backward induction, is a technique to solve dynamic optimization problems. The technique is based on the idea of separating a dynamic optimization problem (e.g. timing of an investment project) in a series of static sub-problems which are easier to be solved than the overall problem (Eeckhoudt et al. 2005; Peters 2016; Ross 2011).

Therefore, a sequence of (at least two) decisions in consecutive periods is investigated. The objective is to maximize the expected value of the project payoff. The backward induction is based on the idea that first the last-period problem is solved for every possible outcome depending on the possible range of situations (state variable(s)) at the beginning of the period (Eeckhoudt et al. 2005). Regarding an investment decision, the situation at the beginning could be either 'investment executed' or 'investment delayed'. As there are no consecutive decisions in the last period, there is no continuation value, which accounts for future decisions. The optimal strategy can hence directly be selected for this period as the strategy with the highest project value (Peters 2016).

In the next step, the preceding period is considered by calculating the project values of all possible outcomes for the decision in this period. In case of continuation, the continuation value (e.g. the project value of the optimal strategy) for the succeeding period is added in order to determine the total value. In case of investment execution, there is no further decision in the succeeding period (as the investment can only be executed once), so that the cash flows caused by the investment for both periods can be summed up directly (Ross 2011). Again, the maximum value of the continuation and the execution strategy is then selected and regarded as continuation value for the preceding period. This backward process continues back to the first period under investigation and the strategy with the highest expected value can be derived (Peters 2016).

The process description above is based on a discrete time contemplation. For continuous time problems, the calculations are more complex as the problem results in a partial differential equation, the Bellman equation, which is also called the fundamental equation of optimality (Peters 2016). As this work focuses on discrete contemplations, the continuous calculations shall not be further introduced here. Details are provided for example in the new edition of the original work of Bellman (2013).

3.5.5 Real Option Thinking

Beyond the mathematical computation and consideration of real options, the basic concept of real option thinking shall be briefly introduced, due to its relevance in the given context. Particularly with regard to deriving policy conclusions, it is often not possible to consider all sorts of options and influencing aspects in a detailed mathematical model. In these cases, it may help to consider the idea of thinking in options at least qualitatively.

Menon and Varadarajan (1992) and Pritsch and Weber (2001) describe the conceptual use of ROA as a mental model in the minds of decision-makers: *"Projects and studies commonly provide concepts, assumptions, models, and theories, which can enter into managers' orientations toward priorities, the manner in which they formulate problems, the range of solutions they convey, and the criteria of choice they apply"* (Menon and Varadarajan 1992, p. 56). Leslie and Michaels (1997) also mention the term 'option thinking' in this context.

The effects of real option thinking on environmental investments can be manifold. A very general conclusion of the real option theory is that the real option value increases with increasing uncertainty. As many industrial environmental investments are hardly economically and technically reversible (i.e. a disinvestment would cause a severe effort), the execution of an investment usually includes a loss of options. Therefore, the importance of real options increases with the level of uncertainty that needs to be considered, no matter if the uncertainty is caused by policy, economics, nature, or other sources.

Furthermore, real option thinking is closely linked to behavioral economics. An important aspect in this context is not only the question, whether the implications of real option thinking are correct, but also to which extent decision-makers already think in options or which effects could be achieved if they were trained to do so. This area of future research, as well as policy implications of real option thinking, will be further discussed in section 6.5.

3.6 Application Specific Conclusions

The ROA method has been selected for the investigation of the investment decision in this work, due to its ability to consider (deferral) options. Particularly in the energy sector with its various sources of uncertainty and risk, ROA has been used frequently in recent years. Exemplary case studies are provided by Adkins and Paxson (2016), Balikcioglu et al. (2011), Boomsma et al. (2012), Buurman and Babovic (2017), Detert and Kotani (2013), Eryilmaz and Homans (2016), Fernandes et al. (2011), Kelly et al. (2016), Lee (2011), Linnerud et al. (2014), Maxwell and Davison (2015), Park (2012), Pindyck (2002), Reedman et al. (2006), Ritzenhofen and Spinler (2016), Sekar (2005), Szolgayova et al. (2008), Welling et al. (2015) and Zhu and Fan (2011).

For CO_2 emission reduction applications, an integral approach is frequently chosen. The whole plant, including the abatement options, is taken into account with all relevant cash flows. This appears reasonable because with the implementation of e.g. certificate trading schemes, the market price of CO_2 becomes more flexible and the buying or selling of allowances may gain new costs or revenues. Therefore, a plant operator might vary the operation of his plant depending on the current price of CO_2. For other pollutants such as NO_X, PM or SO_2, which are less targeted by political regulation, the influence is considered a lot lower. Hence, it seems rather unlikely that a market-based or policy imposed price for any of these pollutants will ever be a key influence parameter for a plant operator to adjust his production output.

Therefore, the decision-making approach in this work will focus on the emission control installation with its directly related investments and costs. The consideration of revenues is not necessary, as they are not (or hardly) influenced by the operation of an emission abatement system (Sarkis and Tamarkin 2005).

To form a basis for the implementation of the economic part of the modeling approach (chapter 5), the main characteristics of the considered investment decision and the corresponding options will be introduced and assessed in the following, in order to select an appropriate option valuation technique. Finally, the main research questions for the modeling approach in chapters 4 and 5 will be summarized.

3.6.1 Characteristics of the Option at Hand

Emission abatement investments in industrial facilities are typically of use for the society and economy as a whole but tend to be costly and time-consuming for plant operators and investors. Particularly in the energy sector and in energy-intensive industries, emission abatement investments are usually long-term oriented and cause considerable investments and operating costs (cf. Breun et al. 2012). These investments are not economically advantageous, but enforced by political regulation, hence, not to invest is not an option.

Investors face economic appeals to avoid or delay these investments due to the negative economic impact on their business. In order to analyze investment behavior in this context, it is inevitable not only to consider now or never investment decisions but to integrate the option of waiting to invest. The aim of this work is to investigate, at which point in time the investment should be exercised even though it does not become economically viable, but causes the least negative economic impact on the investing entity.

Furthermore, it shall be concluded, which levers or thresholds policy measures need to target in order to influence industrial investment decisions effectively. When trying to predict investment decisions of plant operators, the economic point of view can be considered by far the most relevant. Therefore, the modeling approach in the following fully relies on economic and company internal investment decision-making criteria (cf. the discussion in 3.4.3).

In the field of emission abatement for large industrial plants, the variety of techniques is rather limited and the selection is often based predominantly on the technical performance of the technology. Therefore, based on traditional investment appraisal, the main questions are which supplier to choose and which technological details to implement.

Nevertheless, the complexity of the investment decision can be enlarged to any extent, as basically all considered cost components, cash-relevant as well as imputed cost elements, can be considered uncertain. It is inevitable to focus on a certain number and extent of uncertainties in order to understand and assess the results properly.

From an option valuation perspective, the considered application, i.e. the option to defer an environmental investment, can be classified as a dividend-free American call option. The investment decision can be made anytime between the start and the end of the decision-making period.[22] For investors or plant operators, it is usually sufficiently accurate to consider discrete time steps, as investment decisions are typically made at certain times, i.e. the end of a month, a year, etc., and are not continuously reviewed (Brach 2003).[23]

[22] The decision-making period can be limited by the regulation in force, e.g. if a certain threshold needs to be met until a certain date, or by the plant operator according to his needs with regard to the considered forecasts and the decision horizon.

[23] Even though the decision itself may be made at any time, it is considered accurate enough to allocate investment decisions at certain time steps.

Therefore, the option at hand can also be defined as a series of European call options. After every period (e.g. one year), the option can either be executed or it expires. If it expires, a new European option starts, lasting until the end of the next considered period.

In common real option applications, the real option analysis is implemented as an optimal stopping problem, which aims at defining the threshold value *PV** at which the option should be executed. These problems, however, do not consider an obligation to invest. Instead, it can be optimal never to invest, i.e. never to execute the option if the project value *PV* never reaches *PV**.

In this study, however, the investment needs to be executed at the latest by the end of the decision-making period. Therefore, the investment threshold *PV** may vary among different periods, as the choice of possible actions is restricted and becomes increasingly limited towards the end of the decision-making period. Therefore, a standard solution of a continuous or discrete time optimal stopping problem is not applicable in the given case (cf. e.g. Dixit and Pindyck 1994). Instead, a rolling-horizon approach will be implemented which focusses on the question of whether to invest now or to delay the investment to a future period (without predefining the optimal investment period).

The uncertain environment leads to a dual character of the investment decision. A delay of the investment may cause savings compared to an immediate investment, due to technical developments, longer lifetimes or simply the time value of money. However, a delay may also cause losses, for example in case of discontinued funding schemes or increasing investments or costs, e.g. caused by increasing demand in the market. If no significant fluctuations of the total project value are to be expected, an environmental investment, which does not gain revenues, is delayed as much as legally feasible, ceteris paribus. Therefore, disruptive settings need to be considered in order to enable an economically reasonable advancing of the investment. Such disruptive settings could be the discontinuation of public support schemes, the implementation of fees or taxes or massive shifts in the market structure.

Consequently, in this study, the primary question for an investor is, whether the financial risk of a delayed investment supports an advanced investment. The 'price' of the early investment is in the following defined as the imputed interest on the CAPEX.

The option of shutting down a plant due to the cost of emission abatement shall not be considered in the following. Even though this option exists in theory as well as in practice, this study focusses on the question when to invest after a principal investment decision has been made. More complex options such as shut-down or staged investments are also conceivable and therefore suggested as future extensions of the work at hand.[24]

3.6.2 Selection of an Appropriate Option Valuation Method

Current ROA related research in the field of energy and environment primarily focuses on the valuation of options, mainly by developing increasingly sophisticated models (cf. the literature mentioned in 3.6). Despite this intensive research in the field, practical applications of ROA in industry are scarce. Ampofo (2017) analyzes causes for this situation with special regard to the Australian mining sector, a sector that is also strongly influenced by environmental policy. One outcome of this research is that there is, from an industrial point of view, a need to find a compromise between complexity and accuracy. Lambrecht (2017) supports this statement while listing several more limitations and drawbacks of ROA with regard to its practical application. It goes beyond the scope of this work to present and analyze them in detail. However, the conclusion drawn thereof is to focus this work on the development of a transparent, yet reliable methodology.

[24] An exemplary study is provided in Chronopoulos et al. (2016), the importance of staging options and choices as a key element of strategy is also described in Hambrick and Fredrickson (2001) and Trigeorgis and Reuer (2017).

Due to the focus of this work on study-level projects, several simplifications and assumptions appear acceptable, such as the assumption of an arbitrage-free perfect market. Regarding the option valuation technique to be selected, the Black and Scholes equation and its approximation procedures are not considered an appropriate solution for the underlying application, as many simplifications and manipulations would be necessary to convert the original problem in a solvable form. Particularly the difficulty to solve multidimensional problems or non-standard stochastic processes is considered critical. Beyond these issues, Brach (2003) lists more detailed explanations why the Black-Scholes equation is hardly suitable for most practical real option applications.

Option pricing trees are frequently applied in real options analyses, yet they tend to become very complex in case of multidimensional problems with a broad variety of future states.[25] Therefore, they are not considered appropriate for the given application either.

From a theoretical point of view, the LSM approach seems to be the most appropriate methodology for the considered application, if, in the case of multidimensionality, the regarded variables are sufficiently correlated. Specific research with regard to this method is certainly an interesting field for the future.

For the application at hand, however, the standard Monte-Carlo-Simulation based on a series of European options is considered more suitable due to its higher transparency, the lower complexity, and the easier adaptability, even though it remains difficult to predict realistic trends and forecasts, especially for political risks. The transparent implementation and the rather intuitive approach facilitates e.g. sensitivity analyses in order to evaluate the robustness of the results. The most important argument for the use of the standard

[25] Future prices may not only vary between a high and a low level but the whole range in between is possible. Therefore, the number of branches increases uncontrollably if major simplifications shall be avoided.

Monte-Carlo-Simulation, however, is the unspecified degree of correlation of uncertain parameters. The limitation to only investigate scenarios with correlating uncertain parameters shall be avoided by using the standard Monte-Carlo approach, which does not imply such a correlation.

Furthermore, the assessment of investment decisions in the following will be based on a simulation instead of an optimization approach, with the exemption of the dynamic programming on path level (cf. detailed implementation in chapter 5). This facilitates the derivation and assessment of results and allows a detailed understanding of the triggers and key influencing parameters of the decision. It further reduces the computing time and enables thus a contemplation of a large number of scenarios.

With regard to the stochastic processes, the case studies will focus on GBM and jump processes, because disruptive settings are necessary in order to trigger early investments. Therefore, the implementation of a mean-reverting process would be possible, the results, however, cannot be expected to reveal interesting insights, as a limitation of the process fluctuation reduces the risk and hence the incentive to advance an environmental investment.

3.6.3 Summary of the Research Objectives

Table 3-7 summarizes again the main research questions for the implementation of the model in chapters 4 and 5 and the case studies in chapter 6, as mentioned already in the introduction. It shall be emphasized again that for the investigation at hand, not to invest is not an option. Instead, the considered option is to advance the investment compared to the latest possible legally enforced investment date.

Due to the missing economic incentive to invest, disruptive settings are necessary to advance such investments. Examples are ending monetary support schemes, high fees or taxes on emissions, or increasing investment expenditures. Before these investment strategies will be investigated in detail, the calculation of CAPEX and OPEX of the most common NO_X abatement techniques will be assessed in order to derive data for the further investigations and to provide a calculation methodology for all company external entities (e.g. research or political institutions) who lack complete sets of plant data.

Table 3-7: Summary of the main research questions.

Research question	Related chapter
How can the CAPEX and OPEX for NO_X abatement installations in LCP be estimated precisely and efficiently in the early stages of investment planning or by company external entities?	4
How can the optimal timing of the investment be assessed based on the ROA approach?	5
Which policy instruments influence investment decisions in the considered framework in which way?	6

4 Model Part 1: Techno-economic Evaluation of NOx Abatement

The effort and accuracy of study level cost estimates for emission reduction measures in large industrial facilities differ a lot depending on the site-specific application and the perception and organization of the calculating entity. Company internal entities often benefit from broad experiences in other projects or good contacts to suppliers and manufacturers. Research or policy-making institutions, however, typically lack plant-specific data and process knowledge.

Therefore, a calculation approach and corresponding reference data for secondary NO_X abatement techniques in fossil-fueled large combustion plants are presented in the following. It considers solid[1], liquid and gaseous fuels, as well as the secondary NO_X abatement measures SCR and SNCR.

The calculation of primary measures is hardly possible without detailed data about the furnace and boiler configuration. In general, it can be expected that primary measures are cheaper to install and to operate, yet they are, even though continuously improving, usually not sufficient to achieve the legally enforced ELV (Goldring and Riley 2016). Therefore, in most cases, additional secondary measures are necessary.

As the calculation of primary measures mainly depends on the prices of installations such as Low-NO_X-Burners, there is no generally valid calculation methodology for these techniques. Accordingly, the following chapter will focus on secondary measures. Nevertheless, from a practical point of view, the first step to reduce NO_X emissions should be to check the availability and

1 Hard coal or lignite with up to 20 % biomass co-firing.

applicability of primary measures, as they are the most efficient way to abate emissions. Kather et al. (1997) show that even with an already installed SCR system it may be economically advantageous to update primary measures due to the lower operating costs of the SCR system.

The following sections explain the calculation approach for NO_X emission abatement. Starting with a general introduction, the necessary plant-specific characteristics follow, as they are the basis for SCR and SNCR cost calculation. Investment and operating cost calculation for the different techniques are then assessed, including a short discussion about applicability and transferability of the approach. Calculation examples will be provided in the case studies of chapter 6. [2]

4.1 General Approach and Structure

Most LCP operators have an investment-planning department with experts, internal knowledge and broad experiences in this field. These departments may have developed individual methods for the considered task that are, however, not publicly available. Scientists, on the other hand, typically focus on developing new or improved technologies, applications or configurations but not on how to estimate costs for specific applications on a limited database. Therefore, there are only few publicly available methodologies that have been provided by policy-driven or supported entities in order to assist companies or other policy-makers without profound experience. The approach presented in the following is based on two publicly available methodologies for the calculation of investments and costs of secondary NO_X emission abatement techniques.

[2] Parts of this chapter have previously been published in Mayer et al. (2017) and TFTEI (2015a).

The first methodology was developed and published by TFTEI (Task Force on Techno-Economic Issues). The second one was developed and published by the US EPA (United States of America Environmental Protection Agency). The original version was published in 2002 (US EPA 2002) and lastly amended in 2016 (US EPA 2016).

The TFTEI methodology is based on overall plant and operating characteristics and splits up into an investment estimation and an operating cost calculation afterwards. The calculation of the total investment is based on a specific investment reference value (total investment per MW_{th} installed). It can thus be assigned to method F of Peters' scheme (cf. Figure 3-2). Values from exemplary plants delivered by industry members of the TFTEI group or other publications can be used as reference or benchmarking values if no plant-specific data is available. Economies of scale are not automatically taken into account, as there is no globally valid power factor for the considered applications (Peters et al. 2003). It is recommended to use a reference plant of comparable size in order to minimize discrepancies of this kind. The total annual investment related costs are calculated from economic input parameters such as the depreciation time and the interest rate applicable for the regarded company.

The structure of the US EPA method (US EPA 2002) does not split up in two separate paths but combines the calculation of investment (CAPEX) and operating costs (OPEX). It is a mixture of method B (unit cost estimate) and D (Lang factors for approximation of capital investment) of Peters' scheme. The technical characteristics of the regarded plant are examined and/or calculated in several steps. This method is a lot more detailed and might thus be more accurate. However, the origin of the calculation factors and the cost data is nontransparent. They might be based on assumptions that are not valid for the considered plant. Some of the calculations in this methodology require detailed plant data and tend to dissemble an excessively high level of accuracy, while their influence on the result is very low. Other parameters, however, are highly uncertain or based on strongly simplified factors.

A quantitative comparison of the two methodologies is difficult due to the lack of detailed cost data from existing installations and the technical deviations that are likely to exist between individual plants.[3] As mentioned already, the US EPA method is technically more detailed. This facilitates estimating unknown parameters, as they are more specifically delimited. On the other hand, more parameters are necessary and the calculations are less transparent due to the high influence of empirically determined factors.

The TFTEI method uses fewer input parameters and is thus more flexible[4], but depends strongly on the accuracy of single parameters (in particular the specific investment value). Therefore, errors of estimation may have a stronger impact on the results.

The approach to be presented in the following (cf. Figure 4-1) contains elements of both methodologies even though it is strongly linked with the TFTEI approach, primarily due to the higher transparency, flexibility, and adaptability. Further methods for the calculation of NO_X, PM, SO_2, and other pollutant abatement installations have been published for example by Yelverton (2009) (CUECost - Coal Utility Environmental Cost model) and Carnegie Mellon University (2018) (Integrated Environmental Control Model (IECM)). Their overall structure strongly resembles the already mentioned approaches; hence, they will not be discussed in further detail.

3 If detailed cost data exists, it is often at such a highly aggregated level that no inferences on technical specifications are possible. If detailed technical information exists, usually no cost data is provided so that a comparison of the two methodologies cannot be made without major simplifications and inaccuracies. The results of such a quantitative comparison are thus not expected to be of use for this work.

4 Plant-specific information can directly be incorporated in an input parameter (e.g. high complexity of the retrofit can be included in the specific investment value) whereas the US EPA method would require a separate input parameter or an adaptation of the methodology.

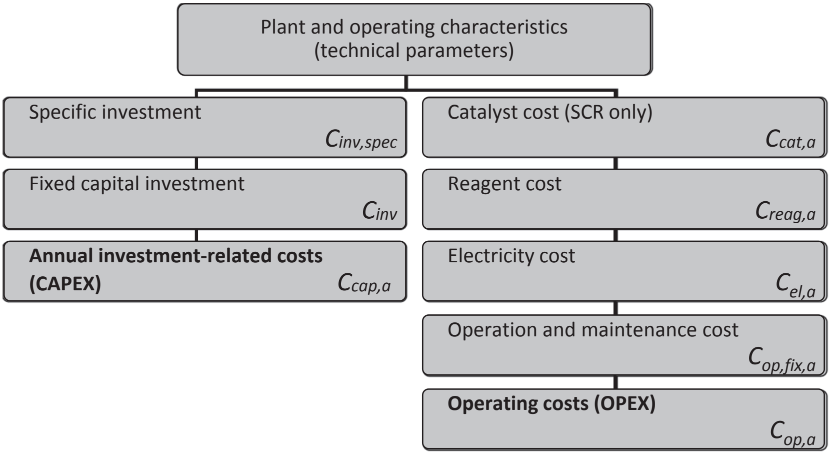

Figure 4-1: Structure of the investment calculation approach for secondary NO_X abatement technologies (cf. Mayer et al. 2015).

4.2 Plant Specifics

The following section provides general plant-specific calculations that are necessary irrespectively of the selected NO_X abatement technology. Most important aspects in this context are details about fuel, flue gas and emission load. The resulting parameters serve as input data for the subsequent cost calculation.

4.2.1 Fuel Consumption and Capacity Factor in Full and Part Load Consideration

The calculation of the fuel consumption is a basic input parameter for many of the following parameters. It is primarily based on the type of fuel in use, the capacity of the plant and the efficiency. The thermal capacity CAP_{th} is linked to the gross electrical output CAP_{el}^{gross} via the gross electric efficiency

η^{gross} (cf. eq. (4-1)). The dependency between gross and net generation and the plant electricity demand P_{el}^{plant} is displayed in equation (4-2).

$$CAP_{el}^{gross} = CAP_{th} \cdot \eta^{gross} \tag{4-1}$$

$$CAP_{el}^{net} = CAP_{el}^{gross} - P_{el}^{plant} \tag{4-2}$$

The hourly mass-based full load fuel consumption $\dot{m}^{fuel}$ (cf. eq. (4-4)) is derived from the fuel energy input $\dot{W}^{fuel}$ (calculated in eq. (4-3)) and the lower heating value of the fuel LHV^{fuel}.

$$\dot{W}^{fuel}\left[\frac{MJ}{h}\right] = CAP_{th}[MW] \cdot 3600 \left[\frac{s}{h}\right] \tag{4-3}$$

$$\dot{m}^{fuel}\left[\frac{kg}{h}\right] = \frac{\dot{W}^{fuel}\left[\frac{MJ}{h}\right]}{LHV^{fuel}\left[\frac{MJ}{kg}\right]} \tag{4-4}$$

The capacity factor $CAPF$ is defined in equation (4-5) as the factor of full load operating hours per year. The annual electric energy production $\dot{W}_{el,a}$ is derived thereof as displayed in equation (4-6).

$$CAPF = \frac{t_{op,fl}[h/a]}{8\,760\ [h/a]} \tag{4-5}$$

$$\dot{W}_{el,a}\left[\frac{MJ}{a}\right] = CAP_{th,fl}[MW_{th}] \cdot CAPF * \eta_{fl}^{gross} \cdot 31536000 \left[\frac{s}{a}\right] \tag{4-6}$$

$$WF = \frac{t_{op}[h/a]}{8\,760\ [h/a]} \tag{4-7}$$

The working factor WF represents the ratio between total operating hours and the total number of hours per year, disregarding the load level (cf. eq. (4-7)). It is of relevance if part load operation is considered, as described below. In case of exclusive consideration of full load operation, the working factor equals the capacity factor.

4.2.1.1 Full load consideration

In the case of exclusive full load consideration, the number of full load hours can be used directly for further calculations. As mentioned already, $t_{op,fl}$ equals t_{op} in this case. The accuracy of this consideration depends primarily on the operating scheme of the plant as not only part load operation but also startup and shutdown processes are neglected (cf. 2.1.3.3). The calculation and data collection effort, however, is comparably low. Table 4-1 contains full-load operating hour ranges for typical power plant classifications that can be used for orientation. It is, however, not necessarily the case that base load plants have the highest share of full load hours. Due to increasing feed-in of fluctuating renewable energy, base-load plants tend to be operated in part load mode more frequently (cf. e.g. Nalbandian-Sugden 2016).

Table 4-1: Plant classification according to Strauss (2016).

Plant classification	Full-load hours per year
Base load	> 5000 h/a
Medium load	2000 - 5000 h/a
Peak load	< 2000 h/a

4.2.1.2 Part load consideration

As described above, most LCP are not continuously operated at full load. Demand fluctuations need to be regulated by adjusting the output of the plant. Due to the increasing and in some countries prioritized feed-in of renewable energy (cf. International Energy Agency 2014), more and more medium- and base-load plants need to adjust their output to avoid network congestions. Therefore, the plants are operated at lower than the nominal load levels. Part load operation affects not only the energy output but also the electric efficiency and the formation of pollutants. Hence, the part load approach allows the consideration of part load operation by providing input data of up to five different load levels as shown exemplarily in Table 4-2.

Table 4-2: Exemplary plant data for different part load levels.

Load level	Annual hours [h/a]	Gross electric efficiency η^{gross}	NO_X emissions at boiler outlet [mg/Nm³]
500 MW (full load)	3000	39%	400
400 MW (80%)	1000	37%	400
350 MW (70%)	500	36%	400
300 MW (60%)	2000	35%	400
250 MW (50%)	500	34%	400

Taking the number of hours assigned to every load level j and the change of gross electric efficiency into account, eq. (4-8) allows calculating an equivalent number of full load hours $t_{op,fl,eq}$. This value can be used in equation (4-5) to determine the capacity factor. As discussed in section 2.1.3.2, the minimum load level is hardly reduced below approximately 40 %[5] in order to avoid additional measures to maintain combustion quality and security. The total operating hours for the calculation of the working factor (cf. eq. (4-7)) are the sum of the working hours at every load level j provided in Table 4-2.

$$t_{op,fl,eq} = \sum_j t_{op,j} \cdot \frac{\eta_{fl}^{gross}}{\eta_j^{gross}} \cdot \frac{CAP_{th,j}}{CAP_{th,fl}} \tag{4-8}$$

The efficiency loss is plant-specific and difficult to calculate. However, in typical applications, it has been shown that the loss in efficiency from peak load to about 40 % load is in the range of 3-5 %, under extraordinarily bad

5 The minimum load may be significantly lower for new and/or technologically advanced or specifically adapted plants (cf. Sloss 2016).

conditions up to 10 % (cf. Chalmers and Gibbins 2007; Strauss 2016). The formation of NO_X during part load operation was described in chapter 2.1.3.2 – it is expected to remain approximately constant due to the interfering effects of lower temperature and lower combustion efficiency (Kather et al. 1997). This statement, however, does not incur the effects of startup and shutdown. Depending on the frequency of startups and shutdowns, an application specific consideration may become necessary.

4.2.2 Flue Gas Volume

The specific flue gas composition at boiler outlet can partly be derived of the fuel composition. Depending on the availability of information about the fuels in use, a detailed or a statistic approach can be selected. Solid, liquid and gaseous fuels have different physical characteristics and need to be distinguished. The different approaches are presented in the following and can be chosen according to the needs and the suitability of the underlying application.

Table 4-3: Reference values for air/fuel ratios in different types of furnaces (Strauss 2016).

Furnace type	λ
Oil-fired furnaces	1,03-1,15
Gas-fired furnaces	1,05-1,10
Coal-fired furnaces	
Dry furnace	1,20-1,30
Slag-tap furnace	1,15-1,25
Grate stoker furnace	1,30-1,40
Fluidized bed combustion	1,10-1,30

One important parameter for all sorts of fuels is the air-fuel ratio λ. This parameter affects various chemical reactions within the burner and boiler, and thus influences the combustion of the fuel, formation, and reduction of pollutants and the composition of the flue gas. Table 4-3 provides a range of values for different fuels and furnaces that can be regarded as reference values even though the actual values in a specific plant might differ.

4.2.2.1 Solid and Liquid Fuels

Two of several possibilities for estimating flue gas volumes of industrial boilers will be presented in the following. The first one is a detailed approach based on the chemical composition of the fuel that will be introduced in order to generate an understanding of the combustion mechanisms.

The second one is a statistic approach introduced by Strauss (2016) that delivers good approximating results based on only one input parameter, the lower heating value. This approach will be applied in the case studies of the following chapters as it is considered likely that detailed information about the fuels in use is not yet available during the early planning stages of an investment project. Furthermore, the origin and quality of fuels may vary during the operating time of an installation and thus limit the validity of the results of detailed approaches.

4.2.2.1.1 Detailed approach

This approach is published in detail in Strauss (2016) and in comparable form also in other basic literature considering industrial combustion (cf. eg. Joos 2007). The basis for the calculation is the composition of the water and ash free (waf) fuel. Elementary analyses provide mass fractions of the relevant elementary components carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur (S) (CHONS). Supposing complete combustion, specific flue gas volumes can be calculated from these CHONS data by mass balancing, considering the following assumptions:

- Full oxidation of carbon to CO_2, no existence of CO or elementary C
- No oxidation of nitrogen to nitrogen oxides
- Full oxidation of sulfur to SO_2, no existence of SO_3 and higher sulfur oxides or elementary sulfur.

The error introduced by these assumptions is existing, but expected to be rather small, if the combustion process is controlled properly. Yet, if values for NO_x, CO, and SO_3 exist[6], adjustment calculations can be added. Adjustments for elementary carbon in ash may be meaningful due to its impact on the flue gas volume and will, therefore, be considered in the following.

Table 4-4: Exemplary composition of some important hard coals and liquid fuels used in the LCP sector (TFTEI 2015a) [% by weight, HHV: higher heating value].

Coal Mine	Country	Elementary composition (waf)					Ash	Moist.
		C	H	O	N	S		
Cerrejon	Columbia	83.40	4.95	9.47	1.37	0.81	8.41	11.83
Middelburg	South Africa	82.44	5.02	10.43	1.38	0.73	13.55	7.42
APC	Australia	88.58	4.73	4.22	1.46	1.00	11.12	10.27
Bachatsky	Russia	87.03	4.66	5.36	2.58	0.37	9.52	10.22
Bailey	USA	84.35	5.58	6.05	2.09	1.74	7.00	7.00
Blackwater	Australia	86.48	4.93	5.71	1.95	0.93	14.16	8.79
Douglas	South Africa	83.30	5.11	9.47	1.42	0.70	13.75	7.65
Elandsfontein	South Africa	88.16	4.86	4.91	1.43	0.64	12.74	9.00
Kleinkopje	South Africa	85.02	4.74	7.33	2.19	0.72	14.49	7.71
Kromdraai	South Africa	81.85	5.03	10.81	1.36	0.95	13.36	7.79
Liquid fuel type	HHV [MJ/kg]	Elementary composition (waf)					Ash	Moist.
		C	H	O	N	S		
Crude oil	n/a	83-87	10-14	0.05-1.5	0.1-2	0.05-6	<1	<0.1
Gasoline	45.7	87	13	n/a	n/a	n/a	n/a	n/a
Diesel	47.0	84-86	13-15	n/a	n/a	<0.02	n/a	n/a
Biodiesel	40.0	77	12	11	n/a	0.01	n/a	n/a
Heavy fuel oil*	43.0	86-88	8-10	n/a	n/a	1-5	0.50	0.1

* The sulfur content of commercial fuel oil, especially heavy fuel oil, varies strongly, as it is determined by refinery operations. Typically, it can be separated into low (<0.5 %), medium (0.5-2 %) and high sulfur (>2 %) heavy fuel oil.

6 The existence of data may also include reasonable assumptions, based on e.g. detailed modeling or experiments.

The lower heating value (LHV) of coal can be derived from its CHONS-characteristics according to different statistic equations that have been published over time. One of the most common equations (cf. (4-9)) was introduced by Dulong and modified by Boie (cf. Lenz 1987; Styczynski et al. 2014), with x_k representing the mass fraction of element k corrected for ash and water contents.[7]

$$LHV^{coal}\left[\frac{MJ}{kg}\right] = 33.91 \cdot x_C + 93.87 \cdot x_H + 10.47 \cdot x_S - 15.18 x_O - 2.44 \cdot x_{H2O} \quad (4\text{-}9)$$

The lower heating value of light and heavy fuel oil can be calculated in good approximation according to empiric equation (4-10), with ρ_{oil} representing the density [kg/l] at 15°C (Strauss 2016).

$$LHV^{oil}\left[\frac{MJ}{kg}\right] = 52.92 - 11.93 \cdot \rho^{oil} - 0.29 \cdot x_S \quad (4\text{-}10)$$

These equations (as well as comparable ones of other authors) are approximations based on several assumptions and statistic data. They are thus able to deliver approximate results for many purposes. However, if precise data of the fuel in use is available, these values should be preferred.

The carbon-in-ash fraction x_{cia} represents the part of the total carbon input that is not oxidized but remains in the ash. This carbon share in the ash has to be subtracted from the carbon mass fraction used for the calculation of the flue gas volume, as it does not contribute to the combustion. In general, the carbon-in-ash content varies depending on the fuel as well as on burner and boiler characteristics.

[7] Elementary analyses are usually provided water and ash free (*waf*). For the following calculations, the mass fractions need to consider the water and ash masses; therefore, x_k needs to be corrected if given at *waf*-level.

Standards for fly-ash usage in the construction industry limit the carbon-in-ash content to a maximum of 5-15 % by weight[8]. Above this limit, fly-ash cannot be sold but needs to be landfilled at considerable costs (Dong 2010). Furthermore, the carbon-in-ash does not contribute to combustion and thus lowers the fuel efficiency. Therefore, power plants envisage operation below the limitations, usually between 2 % and 5 % (TFTEI 2015a). Equations (4-11) and (4-12) show the calculation of the adjusted carbon mass fraction ($x_{C,adj}$) and the total mass of ash (x_{ash+C}) for the following computations of the flue gas volume.

$$x_{ash+C}\left[\frac{kg_{ash+C}}{kg^{fuel}}\right] = x_{ash} + \left(\frac{x_{ash}}{(1-x_{cia})} - x_{ash}\right) \tag{4-11}$$

$$x_{C,adj}\left[\frac{kg_{C,adj}}{kg^{fuel}}\right] = x_C - x_{cia} \cdot x_{ash+C} \tag{4-12}$$

The total flue gas stream consists primarily of the combustion products plus nitrogen and oxygen[9] of the excess air. Strauss (2016) provides a methodology for calculating the specific flue gas volume per kg fuel under normal conditions (0°C, 1 atm) from the elementary CHONS-composition corrected for ash and water content[7]. All specific volumes provided below are given in [Nm^3/kg_{fuel}]. Equation (4-13) displays the calculation of the specific dry flue gas volume $v_{fg,stoi}^{dry}$ under stoichiometric combustion conditions, while equation (4-14) contains the calculation of the corresponding specific dry combustion air volume.

$$v_{fg,stoi}^{dry} = 8.899 \cdot x_{C,adj} + 20.96 \cdot x_H + 3.32 \cdot x_S + 0.80 \cdot x_N - 2.64 \cdot x_O \tag{4-13}$$

$$v_{air,stoi}^{dry} = 8.899 \cdot x_{C,adj} + 26.514 \cdot x_H + 3.342 \cdot x_S - 3.340 \cdot x_O \tag{4-14}$$

8 These standards vary among nations and customers, some examples are mentioned in Dong (2010).

9 The flue gas contains oxygen as the combustion is usually operated with excess air, i.e. with an excess air ratio λ above 1.

The equations (4-15) and (4-16) contain the conversion from dry to wet gas volumes with x_{H2O} representing the mass share of water of the wet air.

$$v_{air,stoi}^{wet} = v_{air,stoi}^{dry} \cdot (1 + x_{H2O}) \tag{4-15}$$

$$v_{fg,stoi}^{wet} = v_{fg,stoi}^{dry} + x_{H2O} \cdot v_{air,stoi}^{dry} \tag{4-16}$$

The calculations of the specific volumes at current excess air ratio λ are displayed in equation (4-17) and (4-18).

$$v_{air,\lambda}^{wet} = \lambda \cdot v_{air,stoi}^{wet} \tag{4-17}$$

$$v_{fg,\lambda}^{wet} = v_{fg,stoi}^{wet} + (\lambda - 1) \cdot v_{air,stoi}^{wet} \tag{4-18}$$

The wet flue gas volume is important to calculate several operating cost components, which are based on actual flue gas volumes such as the costs resulting from the pressure drop caused by secondary measures. Emission limit values, however, are defined as emission loads per dry flue gas volume at standard conditions (0°C and 1 atm) and at legally defined reference oxygen concentration. Therefore, it is important to calculate the moisture content of the flue gas and to differentiate between the wet and dry flue gas volume flows $v_{fg,\lambda}^{wet}$ and $v_{fg,\lambda}^{dry}$.

4.2.2.1.2 Statistic approach

The gathering of detailed fuel data in the early stages of investment planning may be difficult. Therefore the statistic approach introduced by Strauss (2016) is a good compromise to estimate flue gas parameters without having detailed fuel data at hand. The quality of the results depends on the application. In case it meets the typical characteristics of the sector, the results can be very accurate.[10]

[10] Strauss (2016) showed in a calculation example a deviation between the statistic and the detailed approach of less than 1 %.

If, however, one or more parameters such as the carbon in ash content, the formation of CO instead of CO_2, the sulfur content of the fuel, fuel composition in general, etc., differ considerably from typical reference values, the accuracy of results is expected to decrease.

Equations (4-19) and (4-20) display the calculation of the stoichiometric dry flue gas and combustion air volumes for coal, based on the lower heating value *LHV* of the coal. The conversion in wet flue gas and flue gas at excess air ratio λ works similar to the detailed approach explained in equations (4-15) to (4-18).

$$v_{fg,stoi}^{dry}\left[\frac{Nm^3}{kg^{coal}}\right] = (0.2377 \cdot LHV^{coal} + 0.449)\left[\frac{Nm^3}{kg^{coal}}\right] \tag{4-19}$$

$$v_{air,stoi}^{dry}\left[\frac{Nm^3}{kg^{coal}}\right] = (0.3163 \cdot LHV^{coal} + 0.566)\left[\frac{kg^{air}}{kg^{coal}}\right] \cdot \frac{1}{\rho^{air}}\left[\frac{Nm^3}{kg^{air}}\right] \tag{4-20}$$

Equations (4-21) and (4-22) are the equivalent of equations (4-19) and (4-20) for fuel oil combustion and can also be converted into wet streams at excess air ratio as described above.

$$v_{fg,stoi}^{dry}\left[\frac{Nm^3}{kg^{oil}}\right] = (0.225 \cdot LHV^{oil} + 1.119)\left[\frac{Nm^3}{kg^{oil}}\right] \tag{4-21}$$

$$v_{air,stoi}^{dry}\left[\frac{Nm^3}{kg^{oil}}\right] = (0.3437 \cdot LHV^{oil} - 0.425)\left[\frac{kg^{air}}{kg^{oil}}\right] \cdot \frac{1}{\rho^{air}}\left[\frac{Nm^3}{kg^{air}}\right] \tag{4-22}$$

4.2.2.2 Gaseous Fuels

For gaseous fuels,[11] there is a detailed and a statistic approach as for solid and liquid fuels. In the case of gaseous fuels, however, the detailed composition is often not known whereas the LHV is provided by most suppliers. Therefore, the statistic approach is described below, while the detailed approach can be examined in TFTEI (2015a) if needed.

The statistic approach for gaseous fuels is very similar to the one for solid and liquid fuels. Equations (4-23) and (4-24) provide the specific flue gas and combustion air volumes. They can be converted to the specific volumes of wet gas at current excess air ratio by applying equations (4-15) to (4-18) as described above.

$$v_{fg,stoi}^{dry}\left[\frac{Nm^3}{kg^{gas}}\right] = \left(0.2249 \cdot LHV^{gas} + 0.6476\right)\left[\frac{Nm^3}{kg^{gas}}\right] \tag{4-23}$$

$$v_{air,stoi}^{dry}\left[\frac{Nm^3}{kg^{gas}}\right] = \left(0.3443 \cdot LHV^{gas} - 0.063\right)\left[\frac{kg^{air}}{kg^{gas}}\right] \cdot \frac{1}{\rho^{air}}\left[\frac{Nm^3}{kg^{air}}\right] \tag{4-24}$$

For gaseous fuels, this approach is expected to be more accurate than for solid and liquid fuels, as fewer critical influencing parameters need to be considered. The carbon in ash content is negligible because gases hardly contain ash. Furthermore, gases typically contain less undesirable components such as sulfur or water. Yet, due to the fluctuating composition of natural and by-product gases, it may be more difficult to determine and monitor the LHV exactly if it is not provided by the supplier.

[11] Gaseous fuels are primarily natural gas, yet by-products of other industrial processes are also possible (e.g. converter gas in steel production facilities).

4.2.2.3 Part Load Consideration

The calculation of the flue gas volume for all fuels needs to be adapted in case of part load consideration. The total annual flue gas volume is the sum of the flue gas volume at every considered load level *j* (cf. eq. (4-25)).

$$\dot{V}_{fg,\lambda,wet,\mathrm{a}} = \sum_{j} \dot{V}_{fg,\lambda,wet,\mathrm{a,j}} \quad (4\text{-}25)$$

In order to calculate the flue gas volume per load level, the annual fuel consumption per load level needs to be calculated first, as the fuel consumption depends on the efficiency of the combustion that varies among different load levels (Sloss 2016). Equation (4-26) displays the calculation of the fuel consumption per hour and load level. The annual fuel consumption per load level results from equation (4-27). The accumulated consumptions of the considered load levels account for the total annual fuel consumption (cf. eq. (4-28)).

$$\dot{m}_{h,j}^{fuel}\left[\frac{kg}{h}\right] = \frac{CAP_{th,j}[MW_{th}]}{LHV^{fuel}\left[\frac{MJ}{kg}\right]} * 3600\left[\frac{s}{h}\right] \quad (4\text{-}26)$$

$$\dot{m}_{a,j}^{fuel}\left[\frac{kg}{a}\right] = \dot{m}_{h,j}^{fuel}\left[\frac{kg}{h}\right] * t_{op,j}\left[\frac{h}{a}\right] \quad (4\text{-}27)$$

$$\dot{m}_{a}^{fuel}\left[\frac{kg}{a}\right] = \sum_{j} \dot{m}_{a,j}^{fuel}\left[\frac{kg}{a}\right] \quad (4\text{-}28)$$

The dry and wet flue gas volumes per hour and per year are calculated according to equations (4-29) to (4-32) by inserting the results achieved from the calculations above.

$$\dot{V}_{fg,\lambda,h,j}^{dry}\left[\frac{Nm^3}{h}\right] = \dot{m}_{h,j}^{fuel}\left[\frac{kg}{h}\right] * v_{fg,\lambda}^{dry}\left[\frac{Nm^3}{kg}\right] \quad (4\text{-}29)$$

$$\dot{V}_{fg,\lambda,h,j}^{wet} = \dot{m}_{h,j}^{fuel} * v_{fg,\lambda}^{wet} \quad (4\text{-}30)$$

$$\dot{V}^{dry}_{fg,\lambda,a,j} = \dot{m}^{fuel}_{a,j} * v^{dry}_{fg,\lambda} \quad (4\text{-}31)$$

$$\dot{V}^{wet}_{fg,\lambda,a,j} = \dot{m}^{fuel}_{a,j} * v^{wet}_{fg,\lambda} \quad (4\text{-}32)$$

Finally, the flue gas volumes of every load level add up to the total dry and wet flue gas volume per year, as displayed in eq. (4-25).

4.2.3 Integration of Biomass Co-firing

Biomass co-firing is used in an increasing number of plants in order to reduce fossil fuel consumption. Biomass can be co-fired in three different ways: direct, indirect and parallel. In the following, direct co-combustion with coal is considered in order to analyze the effects of biomass co-combustion compared to the combustion of pure fossil fuels within the same installation.[12] Both other types of co-combustion would require modifications in fuel preparation and injection into the furnace so that substantial investments are required that reach beyond the scope of this work.

Typical co-firing ratios using direct co-firing make up to about 20 % of the total fuel mass (Smekens 2013). Regarding the type of biomass, only wood is considered. Co-firing of straw and other types of biomass is less common and more complex with regard to flue gas polluting components, such as chlorine, fluorine and higher contents of alkaline metals. Furthermore, these components affect combustion, ash composition and SCR deactivation (Thøgersen and Jensen-Holm 2010). Table 4-5 provides elemental compositions of exemplary wood types.

[12] The limitation on solid fueled plants is because very scarce information exists on co-firing applications with liquid or gaseous fuels. Therefore, it is not possible to derive and validate a methodology for other types of fuels. If the user possesses detailed reference data, it can be used as input data for the succeeding calculations.

Table 4-5: Exemplary elemental composition of different wood types (Bunbury 1925).

Wood type	Composition of exemplary wood (water and ash free)			
	C	H	O	N
Oak	50.64	6.23	41.85	1.28
Beech	50.89	6.07	42.11	0.93
Birch	50.61	6.23	42.04	1.12
Pine	51.39	6.11	41.56	0.94
Spruce	51.39	6.11	41.56	0.94

Co-firing of biomass also affects several cost relevant parameters. In case of NO_X abatement, the specific emission value $m_{NOx,spec}$ is particularly in scope. Regarding the calculation of fuel consumption and flue gas volume, the equations for solid fossil fuels can be applied for biomass, as it contains the same basic ingredients. For calculating the total annual emissions $\dot{m}_{NOx,a}$ from biomass co-firing, the emissions for both pure coal and pure biomass combustion are calculated according to equation (4-33) and (4-34) assuming single fuel combustion.

$$\dot{V}_{fg,\lambda,a}^{dry} = v_{fg,\lambda}^{dry}\left[\frac{Nm^3}{kg_{\ fuel}}\right] \cdot \dot{m}_h^{fuel}\left[\frac{kg_{\ fuel}}{h}\right] \cdot t_{op,fl}\left[\frac{h}{a}\right] \tag{4-33}$$

$$\dot{m}_{NOx,a} = m_{NOx,spec,ref\,O_2}^{dry} \cdot \dot{V}_{fg,\lambda,\mathrm{a}}^{dry} \tag{4-34}$$

In order to derive the flue gas volume of the fuel mix, the specific flue gas volume of biomass combustion is multiplied with the biomass co-firing ratio α and the specific volume of coal with (1- α) (cf. eq. (4-35)).

$$\dot{V}_{fg,\lambda,a}^{dry} = \dot{V}_{fg,\lambda,a}^{dry,coal} \cdot (1-\alpha) + \dot{V}_{fg,\lambda,a}^{dry,biomass} \cdot \alpha \tag{4-35}$$

The effect of biomass co-firing on specific NO_x emissions is highly site-specific, due to the complex formation mechanisms of NO_x. According to the European Commission (2006), NO_X emissions typically decrease with a rising share of biomass co-firing due to the smaller nitrogen content of biomass compared to coal. However, NO_X formation is not only determined by fuel characteristics but also by combustion characteristics and combustion technology. Therefore, a site-specific contemplation of the various influencing factors is necessary in order to derive reliable conclusions.

4.2.4 NOx Emission Calculation

NO_X emission loads cannot be derived by mass balancing, as the formation mechanisms of NO_X are very complex and depend on various parameters such as local temperature, residence time and oxygen concentration (cf. 2.1.2). Therefore, an estimation of NO_X emission levels without a detailed simulation of the power plant is not possible. Consequently, either measured data (in case of retrofits) or reference values for the utilized fuel and technology[13] have to be applied.

4.2.4.1 Average Emission Values

Table 4-6 lists reference values for NO_X emission levels of different plant configurations. However, actual values may differ depending on the operation and control strategy of the plant, the implementation of primary measures and the fuels in use. Therefore, the gathering of precise data is considered crucial for the accuracy and significance of the results.

[13] Especially the boiler configuration and the burner system (low-NO_X burner vs. conventional burner) need to be considered.

Table 4-6: Reference NO_X boiler outlet emissions for solid, liquid and gaseous fossil fuel combustion in boilers and process heaters [mg/Nm³ ref. O_2] (Lecomte et al. 2017; TFTEI 2015a).

		Hard/bituminous coal		Lignite	
		without abatement	with primary measures	without abatement	with primary measures
Dry bottom boiler	Horizontal firing system	1000 - 1500	500 - 650	NA	NA
	Tangential firing system	600 - 900	400 - 650	400 - 700	200 - 500
	Vertical firing system	700 - 900	NA	NA	NA
	Downshot firing system	up to 2000	1000-2000	NA	NA
Wet bottom boiler	Cyclone firing system	1500 - 2500	1000 - 2000	NA	NA
		Liquid fuels		**Gas fired units**	
Uncontrolled		800 - 1000		150 - 400	
Single primary measures		400 - 500		75 - 150	
Multiple primary measures		< 400		< 75	

4.2.4.2 Oxygen Correction

Emission limit values (ELV) are usually expressed at so-called reference oxygen concentrations; therefore, a conversion of the oxygen concentration of flue gases is necessary. Table 4-7 displays the O_2 reference concentrations for ELV in the amended Gothenburg Protocol (UNECE 2013). These reference concentrations, however, vary among different regions and legislations and need to be retrieved from local ELV requirements.

Table 4-7: Reference O_2 concentrations in the amended Gothenburg Protocol (UNECE 2013).

Fuel	Reference O_2-concentration
Solid fuels	6 %-Vol.
Liquid fuels	3 %-Vol.
Gaseous fuels in boilers and process heaters	3 %-Vol.
Gas turbines	3 %-Vol.

In order to assess the compliance with emission limit values, measured specific emissions values $m_{NOx,spec}$ need to be converted in specific emission values at reference O_2 concentration $m_{NOx,spec,refO_2}$ (both values in mg per Nm³) as shown in equation (4-36) with con_{O_2}representing the O_2 concentration in the flue gas (Kolar 1990).

$$m_{NOx,spec,refO_2} = \frac{(21 - con_{O_2,ref})}{(21 - con_{O_2,act})} \cdot m_{NOx,spec} \tag{4-36}$$

As NO_X emission values have to be estimated for many applications, the specific emission value at reference O_2-concentration $x_{NOx,spec,refO_2}$ will be used in the following if not stated otherwise, in order to facilitate the use of the equations. Hence, (4-36) is only relevant for applications with actual measurement data that has to be converted to reference O_2 concentration.

4.2.4.3 Effects of Part Load Consideration

The calculation of NO_x emission loads in the flue gas was described above. In case of part load consideration, however, the specific NO_x emission levels (related to fuel consumption) are also depending on the load level itself, as operation at lower load levels affects combustion temperatures and residence times, which again influence the formation of NO_X. Hence, it needs to be possible to adjust the amount of NO_x emissions at different load levels. Again, a quantitative estimation of the emission loads based on theoretical calculations or mass balancing is hardly possible, due to the complex formation mechanisms. Therefore, the best reference is measured data from existing plants. If precise reference data is not available, it can be assumed that the total emissions at part load operation remain approximately constant, because the efficiency of the plant declines as well as the formation of thermal NO_X, due to lower combustion temperatures (Kather et al. 1997).[14]

Equations (4-37) and (4-38) display the calculation of NO_X emissions per hour and per year at every load level *j*. Due to the complex formation of NO_X, the specific NO_X emissions at every considered load level $m^{dry}_{NOx,spec,ref\,O_2,j}$ have to be provided by the user.

$$\dot{m}^{dry}_{NOx,\lambda,h,j} = \dot{V}^{dry}_{fg,\lambda,h,j} * m^{dry}_{NOx,spec,ref\,O_2,j} \tag{4-37}$$

$$\dot{m}^{dry}_{NOx,\lambda,a,j} = \dot{V}^{dry}_{fg,\lambda,a,j} * m^{dry}_{NOx,spec,ref\,O_2,j} \tag{4-38}$$

The total annual NO_X emissions are then derived from summing up the emissions of the considered load levels (cf. eq. (4-39)).

$$\dot{m}^{dry}_{NOx,\lambda,a} = \sum_j \dot{m}^{dry}_{NOx,\lambda,a,j} \tag{4-39}$$

4.3 Primary Measures

As mentioned above, the cost calculation for primary measures is comparably difficult, as the major share of costs depends on the equipment itself and therefore on supplier prices (cf. Rentz et al. 1999). These are difficult to estimate due to the manifold economic influences, such as demand and supply structures, etc.

14 Cf. also 2.1.2 and 2.1.3.2.

Therefore, the investments are calculated from a specific investment input factor $C_{1°,inv,spec}$ in Euro (or any other currency) per MW_{th} multiplied with the thermal capacity at full load operation (cf. eq. (4-40)).[15] The specific investment has to be derived from existing data, literature values or from supplier bids.

$$C_{1°,inv} = C_{1°,inv,spec} \cdot CAP_{th,fl} \quad (4\text{-}40)$$

Literature values are, however, difficult to gather, due to the local and technology-specific differences among different applications. Exemplary orders of magnitude are provided in Nalbandian (2006) and Wiatros-Motyka and Nalbandian-Sugden (2018) who mention values of about 3 to 25 US-$ per kW, depending on the type of technology, the date of the reference and the complexity of the retrofit.[16]

Operating expenses of primary measures are neglected in the following, due to the difficult estimation and their small share of total costs, particularly compared to the costs of secondary abatement installations (Nalbandian 2006). If the installation of primary measures shall be assessed solely, this is a major simplification. Yet for primary measures, it can be assumed that supplier bids are easier to get so that a detailed cost calculation tool is considered less relevant. The focus of this work and the tool at hand is hence on projects with primary and secondary or only secondary measure installations.

[15] Full load data is used for all design parameters, as the system needs to be capable of full load operation even though the average load may be lower.

[16] The costs can be assumed significantly lower for new installations.

4.4 Selective Catalytic Reduction (SCR)

This chapter explains the details of cost calculation for SCR systems. According to the cost calculation approach presented in chapter 3.1, it starts with investment calculation, followed by the calculation of variable and fixed operating costs. Total costs and the amount of emissions abated will be derived in chapter 4.6 for both, SCR and SNCR systems.

4.4.1 Investment Calculation

Two approaches are considered particularly suitable for investment calculation of SCR systems. The first one is based on specific investments and was developed and published by TFTEI (2015a). The second one is the factor-based approach the US EPA originally published in 2002 (US EPA 2002) with the latest revision in 2016 (US EPA 2016). Despite its actuality, the missing transparency of factorial approaches remains a problem. It is aggravated in the US EPA approach by the use of US customary units that limit the intuitive comprehension and easy conversion of influencing parameters for non-US users.

Consequently, the TFTEI approach forms the basis for the calculation approach presented below. Despite its limitations, it is considered advantageous due to the higher adaptability with regard to user-specific applications, even if exceptional circumstances prevail.[17] Disregarding the approach described below, the results of the US EPA methodology or any other publicly available or company specific methodology can still be used as input data for the second part of the investment decision-making model described in chapter 5.

[17] Its applicability and accuracy (within the accuracy level of +/- 25 %) have been proven by successful applications of industry representatives within the TFTEI group. Yet, due to the sensitivity of the underlying data, these applications remain unpublished.

Equation (4-41) displays the basic investment calculation, again with the total investment as the result of the specific investment multiplied with the thermal capacity at full load operation.

$$C_{SCR,inv} = C_{SCR,inv,spec} \cdot CAP_{th,fl} \tag{4-41}$$

The calculation of the total investment is rather complex, as the detailed delimitation of the specific investment value is often not known. According to Peters et al. (2003), the total investment is meant to contain everything necessary to operate the plant. Miller (2011, p. 436) lists the following important components that need to be considered for SCR applications:

- *“Catalyst and reactor system*
- *Flow control skid and valving system*
- *Ammonia injection grid*
- *Ammonia storage*
- *Piping*
- *Ducts, expansion joints, and dampers*
- *Fan upgrades/booster fans*
- *Air preheater changes*
- *Foundations, structural steel, and electricals*
- *Installation.”*

Following the definition of Peters, the total investment should also include the first fill of reagent tanks and catalyst. Experienced plant operators possessing reference data from preceding projects, may be able to reproduce the components considered in the reference investment value. Less experienced investors or authorities may be struggling to gather reference data at such a detailed level. Regarding publicly available reference values it is hardly possible to provide a universal statement whether the initial fill of catalyst and reagent is considered in the specific investment or not. If the user of the methodology is unsure about the consideration of such cost components, it might be reasonable to consider a contingency factor.

In order to avoid massive under- or overestimation of costs, the following compromise regarding investment calculation is recommended for all applications with unspecific reference data. From a theoretical perspective, it is not perfectly stringent with the definition of investments, but it is considered reasonable in a practical context.

The initial fill of consumables[18] is not added to the total investment, as the investment sum determines not only the capital costs but also the investment related operating costs. Consequently, the full consumption of reagent and catalyst (including the first fill of tanks) is taken into account as operating costs. As mentioned above, more detailed information about the composition of the specific investment value, the size of tanks and the catalyst management strategy can be considered if available. This may lead to minor modifications of the result of equation (4-41).

Publicly available reference values for the specific investment of SCR systems are provided for example in TFTEI (2015a). The average specific investment value in this study is 52.6 [$€_{2010}/kW_{th}$]. However, there is a large range of values that can be considered a strong indication for a varying complexity among different plants, a major influence of plant-specific characteristics[19] and/or inconsistent definitions of the specific investment value. Hoskins (2003) confirms that combinations of these influences also apply frequently.

Another inconsistency is caused by the consideration of all types of fuels. Reis (2010) investigated severe differences between different fuels, providing the following specific investment reference values:

- Coal: 70 €/kW
- Oil: 45 €/kW
- Gas: 50 €/kW.

18 In the case of SCR installations, consumables are primarily catalyst and reagent.

19 E.g. the fuel in use, high-dust/low-dust/tail-end configuration, the thermal capacity, etc.

These values support the average value of the TFTEI study while delivering more detailed information regarding the fuel in use. Therefore, they can be recommended for application if no site-specific data is available. Older US studies by Cichanowicz (2004), Hoskins (2003) and Marano and Sharp (2006) denote slightly higher costs, with approximately 80-150 US-$ per kW. The deviation may be caused by the exclusive consideration of coal plants and the technical and economic development in the meantime between the studies.

The use of reference values for other plant sizes implies a linear investment function. Due to the influence of economies of scale, fixed investment components[20] and surface-based investment expenses[21], a linear investment function is a rather strong simplification. Nevertheless, the non-linearity is not directly taken into account in the following, as there is no globally valid power factor for the considered applications (Peters et al. 2003). Instead, it is recommended to use a reference plant of comparable size or to implement a power factor manually by modifying the specific investment input value according to equation (4-42).

$$C_{inv} = \left(\frac{CAP_{inv}}{CAP_{ref}}\right)^n \cdot C_{ref} \tag{4-42}$$

Typical values for the power factor *n* in the chemical and process industry range between 0.6 and 0.8 (cf. Peters et al. 2003). SCR systems consist of various components, therefore no direct correlation between the investment of the projected system C_{inv} and the reference system C_{ref} can be defined.[22]

20 E.g. project management, R&D, control systems, etc.

21 A subproportional relationship between investment and capacity of an installation often results of the fact that production capacities are volume based whereas investments may be surface based (cf. tanks, pipes, etc.). Therefore, the capacity increases by times three, while the investment only increases by times two, which leads to a non-linear investment function.

22 It would be easier if the main component of the system was one entity such as a reaction tank. SCR systems, however, consist of numerous individual components, such as pumps, injectors, reactors, pipes, etc. with varying complexity depending on the specifics of the plant.

The precise derivation of a realistic power factor is thus very complex and requires a large amount of detailed data.

Further conversions of reference data may be necessary with regard to currency and cost year. Exchange rate fluctuations can be taken into account by considering current or historic stock data. The cost year is relevant due to changing monetary value caused by inflation and deflation and the development of the market price level of the considered components.[23] Various, usually industry-specific indices have been developed to enable conversion between different cost years (Peters et al. 2003). One of these, originally developed for the chemical industry and considered most appropriate for the underlying application, is the Chemical Engineering Plant Cost Index (CEPCI). It is monthly published in the journal "Chemical Engineering" with its latest revision in 2002 (Vatavuk 2002). Table 4-8 displays its annual average values between 1998 and 2016.

Table 4-8: Exemplary CEPCI data (Jenkins 1998-2017).

Cost year	Factor	CEPCI Value	Cost year	Factor	CEPCI Value
2016	1.00	541.7	2006	1.08	499.6
2015	0.97	556.8	2005	1.16	468.2
2014	0.94	576.1	2004	1.22	444.2
2013	0.95	567.3	2003	1.35	401.7
2012	0.93	584.6	2002	1.37	395.6
2011	0.92	585.7	2001	1.37	394.3
2010	0.98	550.8	2000	1.37	394.1
2009	1.04	521.9	1999	1.39	390.6
2008	0.94	575.4	1998	1.39	389.5
2007	1.03	525.4	1997	1.40	386.5

[23] The market price level depends on supply and demand, technological progress and the costs of raw materials and components.

In order to convert costs to the base year (here: 2016), the factor provided in Table 4-8 can be used directly. Conversions between two user-defined years are also possible as displayed in equation (4-43). It is to be noted that the CEPCI is published in US dollars and therefore a conversion into US dollars for both the base year and the target year value is necessary in order to avoid falsifications caused by varying currency conversion rates.

$$C_{year\ \mathrm{a}} = C_{year\ \mathrm{b}} \cdot \frac{CEPCI_{year\ \mathrm{a}}}{CEPCI_{year\ \mathrm{b}}} \quad (4\text{-}43)$$

Another influencing parameter regarding the total investment is the difference between a retrofit and a new installation. New installations are usually considered less costly, as they can be specifically suited to and integrated into the construction of the plant (Reis 2010). The complexity of retrofits differs significantly based on the construction and location of the plant (Wu 2001).

If the complexity of the considered installation in relation to the reference installation is known, it can be taken into account by applying a retrofit factor on the specific investment of the reference plant. Wu (2001) describes deviations of 20 % to 35 % between moderately difficult and difficult retrofits. The difficulty primarily refers to the need for fan upgrades, structural steel, and foundation changes. US EPA (2016) further indicates a deviation of about 20 % between moderately difficult retrofits and new installations. Therefore, a retrofit factor between 0.8 and 1.3 appears reasonable if detailed knowledge about the complexity of the reference plant compared to the projected system is available.

4.4.2 Variable Operating Cost Calculation

The variable operating costs for SCR systems $\dot{C}_{SCR,op,var}$ consist of three major components, as displayed in equation (4-44). According to Yelverton (2009) reagent and catalyst costs ($\dot{C}_{SCR,reag}$ and $\dot{C}_{SCR,cat}$) are the cost components with the highest share, followed by electricity costs ($\dot{C}_{SCR,el}$). Other minor cost components such as disposal of waste[24], costs for small amounts of consumables etc. are not directly considered in the following in order to keep the effort at a reasonable level.

$$\dot{C}_{SCR,op,var} = \dot{C}_{SCR,reag} + \dot{C}_{SCR,cat} + \dot{C}_{SCR,el} \tag{4-44}$$

If detailed data regarding other variable cost components are available, they can be considered as well. Furthermore, a contingency component can be integrated into the fixed operating costs described in chapter 4.4.3. This practice disregards the precise aggregation of costs. However, it may be appropriate to avoid underestimation of costs during early stage investment planning, (cf. Mayer et al. 2017).

4.4.2.1 Catalyst Cost

The catalyst cost comprises of the initial catalyst cost and the catalyst regeneration and/or replacement costs. Apart from the catalyst price, the catalyst cost depends on the catalyst volume, the catalyst lifetime and the catalyst management strategy (cf. chapter 2.2.2.3).

According to Thøgersen and Jensen-Holm (2010), the catalyst deactivation typically ranges between 10 and 15 percent per 10 000 operating hours. It can go up to 19 percent per 10 000 hours in case of biomass co-firing under good process control[25] or even higher, if the process is not specifically controlled. Up to a co-firing rate of approximately 20 percent Jensen-Holm et al. (2009) confirm that the influence of biomass co-firing on deactivation is very low (assuming appropriate control of the process) and can thus be neglected in the following.

[24] The costs for disposal may be negative if residues can be sold. This is hardly relevant for NO_X abatement, yet fly ash or gypsum from particulate matter or sulfur oxide abatement installations can often be sold.

[25] In case of biomass co-firing, injection of fly ash may be necessary to achieve these results.

Catalyst regeneration is very common in recent installations (cf. 2.2.2.3). It requires a spare catalyst layer if regenerations shall be possible without complete plant shutdowns. The regeneration results depend on the type of catalyst, the regeneration process and the degree of poisoning (Wiatros-Motyka and Nalbandian-Sugden 2018). Under good conditions, up to 100 % of the original activity can be regained (Thøgersen and Jensen-Holm 2010). This value is thus assumed in the following.

Equation (4-45) displays the calculation of the catalyst volume V_{cat} based on the specific catalyst requirement $V_{cat,spec}$ in [m³/MW$_{th}$]. The total catalyst lifetime (including regenerations) is calculated in equation (4-46) with the catalyst lifetime without regenerations $T_{cat,h}$, the number of regenerations per catalyst layer N_{reg} and the number of full load hours (either directly determined in the full load approach or the calculated equivalent in case of part load consideration) $t_{op,fl,(eq)}$.

$$V_{cat} = V_{cat,spec} \cdot CAP_{th} \tag{4-45}$$

$$T_{cat,tot,a} = \frac{T_{cat,h} \cdot (N_{reg} + 1)}{t_{op,fl,(eq)}} \tag{4-46}$$

The reference value of the specific catalyst volume has to be carefully selected, as it depends not only on the size of the installation but also on the NO_X reduction rates to be achieved.

If no reference data from a comparable investment is available, an approach to estimate the catalyst volume is provided by US EPA (2016). This approach considers several technically relevant parameters. The equation is presented in (4-47) with the necessary adjustment factors displayed in (4-48) to (4-52). It can be used alternatively or as a benchmarking value to the existing data.

$$V_{cat} = 0.07957 \cdot \frac{\dot{W}_{fl}^{fuel}}{1055} \cdot \eta_{adj} \cdot Slip_{adj} \cdot NOx_{adj} \cdot Sul_{adj} \cdot \vartheta_{adj} \tag{4-47}$$

The original equation displayed in the reference publication has been converted in SI units so that the resulting catalyst volume is calculated in [m³] and the thermal input at full load $\dot{W}_{fl}^{fuel}$ needs to be inserted in [MJ/h]. It is assumed that only one SCR reactor is regarded. The adjustment factors consider the NO_X reduction efficiency η_{NOx} in percent, the allowed ammonia slip in [ppm][26], the concentration of NO_X at the inlet of the SCR NOx_{in} in [lb/MMBtu], the sulfur content of the fuel x_S by dry weight fraction [%] and the flue gas temperature at the reactor inlet ϑ in degrees Celsius.[27]

$$\eta_{adj} = 0.2869 + (1.058 \cdot \eta_{NOx}) \tag{4-48}$$

$$Slip_{adj} = 1.2835 - (0.0567 \cdot Slip\ [in\ ppm]) \tag{4-49}$$

$$NOx_{adj} = 0.8524 + (0.3208 \cdot NOx_{in}) \tag{4-50}$$

$$Sul_{adj} = 0.9636 + (0.0455 \cdot x_S) \tag{4-51}$$

$$\vartheta_{adj} = 13.93 - (0.06771 \cdot \vartheta) + (8.878 \cdot 10^{-5} \cdot \vartheta^2) \tag{4-52}$$

From a technical point of view, the most critical parameter is NOx_{in}, as the value needs to be inserted in [lb/MMBtu]. A direct conversion between [mg/Nm³] and [lb/MMBtu] is not possible, yet Faber Burner Company (2018) provides a calculator for approximate conversions for gas, oil and coal-fired installations from [lb/MMBtu] to [ppm] and Lenntech (2018) provides a further converter for [ppm] to [mg/Nm³] based on the molecular weight of NO_2. A list of frequently used values for NO_2 concentrations in coal-fired plants is displayed in Table 4-9.

26 The equation is only valid for ammonia slip levels between 2 and 5 ppm. Above 5 ppm ammonia slip, the correction factor can be assumed to be 1.

27 The percentage and ppm values have to be inserted directly, i.e. a value of e.g. 2 % or 2 ppm is inserted in the equation as 2.

Table 4-9: Overview of approximate NO_x (NO_2) concentrations in different units for coal-fired plants.

mg/Nm³	ppm	lb/MMBtu
50	24.7	0.0336
100	49.4	0.0672
150	74.0	0.101
200	98.7	0.134
400	197	0.268
600	296	0.403
800	395	0.537
1000	494	0.672

The annualized catalyst cost $\dot{C}_{cat,a}$ is then calculated according to eq. (4-53) based on the cost of the initial catalyst and the cost of regenerations (with the specific catalyst price $c_{cat,spec}$ in [€/m³] and the regeneration price $c_{reg,spec}$ in [€/reg] divided by the total lifetime of the catalyst in years).[28]

$$\dot{C}_{cat,a} = \frac{V_{cat} \cdot c_{cat,spec} + N_{reg} \cdot V_{cat} \cdot c_{reg,spec}}{T_{cat,tot,a}} \qquad (4\text{-}53)$$

Table 4-10 provides some benchmarking catalyst parameters for typical coal-fired plants (TFTEI 2015a). The situation in specific plants, however, may deviate severely from the given numbers, as many parameters, such as fuel quality, mode of operation, catalyst management strategy, boiler design and configuration, flue gas treatment configuration, location of the plant, etc. influence the catalyst characteristics and hence the catalyst cost (Wiatros-Motyka and Nalbandian-Sugden 2018).

[28] The total catalyst cost is considered as operating costs in favor of simplicity, even though other references (e.g. Peters et al. 2003) recommend adding the first fill to the investment.

Table 4-10: Catalyst cost and design data for coal-fired units (TFTEI 2015a).

	Low	High	Unit
Specific catalyst requirement	0.5	0.6	m^3/MW_{th}
Catalyst lifetime	24 000	36 000	h
Number of catalyst regenerations	0	3	-
Specific catalyst price	4 000	5 000	€/m³
Specific catalyst regeneration price	2 500	2 500	€/m³

According to Maier (2010), the catalyst prices undergo strong fluctuations due to a comparatively unstable sellers' market. Therefore, the definition of a long-term valid reference price is difficult. Users of the methodology are encouraged to check current and local price data for new catalyst and catalyst regenerations, if applicable.

A fairly recent reference price for new catalyst of 5 000 to 6 000 US-$/m³ was provided by Cichanowicz (2010) and adopted for the 2016 US EPA Air Pollution Control Cost document (US EPA 2016). Assuming the 2016 average conversion rate of 1.11 US-$/€, catalyst prices of approximately 4500 - 5400 €/m³ result. This reference value is within the same range as the prices listed above. Prices for catalyst regenerations differ as well, depending amongst others on catalyst material, design, and the regeneration technique. McMahon (2006) mentions a typical regeneration price of about 60 % of the price of a new catalyst, which will be assumed as reference value in the following. However, as discussed in chapter 2.2.2.3, catalyst regeneration, protection and management is a major field of ongoing research and development which may lead to short notice variations regarding cost and performance parameters (cf. e.g. Olsen et al. 2017; Wiesel et al. 2017).

US EPA (2016) further discusses the impact of the time value of money with regard to the catalyst cost as the catalyst is usually in operation for several months or years. Therefore, the application of a future worth factor based on the replacement interval of the catalyst is recommended in this reference. The EPA approach, however, neglects the possibility of catalyst regenerations, which further complicate the consideration of the time value of money. Due to the basic goal of the work at hand – the derivation of reasonable early stage cost estimations – it is considered acceptable to neglect the time value of money in favor of the methodological simplification. The influence of the time value of money is furthermore considered comparably low, as the replacement intervals are typically several times shorter than the operating time of the SCR system itself.

4.4.2.2 Reagent Cost

Reducing agents are necessary for the chemical reduction of NO_X. The most commonly used reagents are ammonia and urea. According to Fisher (2002) and US EPA (2016), the type of reagent has a major influence on the cost structure of the system with urea causing higher total costs. As ammonia is the most commonly used reagent,[29] the following section primarily covers ammonia applications so that the reference values need to be scrutinized if applied for urea applications.

From a chemical perspective, one mole of ammonia is needed for the reduction of one mole of NO, while two moles of ammonia are necessary per mole of NO_2 (cf. chapter 2.2.2).[30] The stoichiometric ratio factor *SRF* (cf. eq. (4-54)) defines the amount of reagent to be injected to abate the envisaged amount of NO_X. In large combustion plants, 90 % to 95 % of NO_X in the flue gas is NO, therefore, the theoretical stoichiometric ratio for a total reduction of NO_X is around 1.05.[31] An almost linear relationship between the consumption of reagent and the amount of NO_X removed can be assumed up to about 85 %

29 In the study of US EPA (2016), about 80 % of the investigated 230 utility boilers use ammonia as reagent. In other regions, safety requirements, which are more critical for ammonia, may influence the market share and the cost structure.

30 In technical applications, the stoichiometric ratios deviate from these values. The details will be explained below.

31 This value is valid if ammonia is used as reagent. For urea, the SRF ranges around 0.525.

NO_X reduction (Rosenberg, Oxley 1993). Above 85 %, the removal efficiency begins to decrease due to reaction rate limitations and a higher share of ammonia is required for additional NO_X removal (US EPA 2016). Yet the additional amount of ammonia is limited by the permitted ammonia slip, which increases with higher stoichiometric ratios due to the higher content of ammonia and therewith increasing rates of incomplete reaction (Schultes 1996). At the same time, this effect limits the maximum reduction efficiency of the technology. Stoichiometric ratios factors for practical use in SCR systems vary typically between 0.8 and 0.9. (TFTEI 2015a; US EPA 2016)

$$SRF = \frac{moles\ of\ reagent\ injected}{moles\ of\ NOx\ to\ be\ removed} \tag{4-54}$$

The reaction efficiency is further influenced by the temperature, the degree of mixing, the residence time and the control of the complex reactions including the catalyst management (Schultes 1996). A simplified calculation of the optimal SRF is not possible due to these complex influences. It is thus recommended to use reference values from literature (as mentioned above) or from comparable installations if available.

Equations (4-55) and (4-56) display the calculation of the mass of NO_X to be abated and the therefore necessary mass of reagent $\dot{m}_{reag}$. The NO_x concentrations in eq. (4-55) need to be inserted at actual oxygen concentration (cf. 4.2.4.2) because the annual flue gas volume is calculated at actual oxygen concentration. Consequently, if the SCR is meant to meet a specific ELV ($\rho_{NOx,out,ref\,O_2}$) expressed at reference oxygen concentration, this ELV must be divided by the oxygen correction factor (cf. eq. (4-36)) to derive the permitted emissions at actual oxygen concentration ($\rho_{NOx,out}$). Both NO_X concentration values ($\rho_{NOx,in}$ and $\rho_{NOx,out}$) are to be inserted in mass per Nm^3.

$$\Delta\dot{m}_{NOx,a} = \left(\rho_{NOx,in} - \rho_{NOx,out}\right) \cdot \dot{V}_{fg,dry,a} \tag{4-55}$$

$$\dot{m}_{reag,a} = \frac{M_{reag}}{M_{NOx}} \cdot \Delta\dot{m}_{NOx} \cdot SRF \tag{4-56}$$

The molar masses *M* to be inserted in eq. (4-56) are displayed in Table 4-11. Scientific literature is not distinct in whether to use the value for NO or NO_2 for NO_X. US EPA (2016) uses the value for NO_2 while Strauss (2016) uses the value for NO. The appropriate value should be selected according to the associated emission data. As discussed above, emission values are often converted to NO_2 in order to ensure comparability. If this has been done with the emission data, the molecular weight of NO_2 has to be applied. If unconverted data is used, the application of the molecular weight of NO is recommended, as the majority of NO_X in the flue gas is NO.

Table 4-11: Molar masses of NO_X and reagents.

Element	Molar mass [kg/kmol]
NO	30
NO_2	46
Ammonia (NH_3)	17
Urea (CH_4N_2O)	60

Reagents are often delivered and injected as aqueous solutions. Typical concentrations for delivery and storage $s^{storage}$ are 50 % for urea and 29.4 % for ammonia (US EPA 2016). Before injection into the system, the reagents may be further diluted with water to reach a lower injection concentration $s^{injection}$. This dilution facilitates appropriate mixing between flue gas and reagent (Heide 2012b). Recent publications such as US EPA (2016) (in contrast to US EPA (2002)) disregard this effect, especially for SCR applications. There may be two reasons, either the dilution of reagents becomes less common or the monetary effect of this dilution is negligible. If no further dilution before injection shall be considered, the storage and injection concentration are equal.

Equations (4-57) and (4-58) calculate the mass flow of diluted reagent $\dot{m}_{reag,dil}$ at storage and injection concentration, depending on the mass flow of pure reagent. The mass flow of water to be added in order to obtain the dilution concentration for injection is calculated in equation (4-59). The total annual reagent cost results of the annual consumption and current market prices of reagent and water (cf. eq. (4-60)).

$$\dot{m}_{reag,dil}^{storage} = \frac{1}{con^{storage}} \cdot \dot{m}_{reag} \tag{4-57}$$

$$\dot{m}_{reag,dil}^{injection} = \frac{1}{con^{injection}} \cdot \dot{m}_{reag} \tag{4-58}$$

$$\dot{m}_{wat} = \left(\frac{1}{con^{injection}} - \frac{1}{con^{storage}}\right) \cdot \dot{m}_{reag} \tag{4-59}$$

$$\dot{C}_{reag,a} = \dot{m}_{reag,dil,a}^{storage} \cdot c_{reag,dil}^{storage} + \dot{m}_{wat,a} \cdot c_{wat} \tag{4-60}$$

Himes (2004) provides more details on market price developments of reagents. As both ammonia and urea are produced from natural gas, their prices fluctuate proportional to natural gas prices (cf. Cichanowicz 2010; Himes 2004). Table 4-12 provides reference values for different reagent prices (Himes 2004).

Table 4-12: Reagent price examples and comparisons (Himes 2004) [Original numbers are in US-$ and were converted in EUR using the 2016 average exchange rate of 0.90 €/US-$].

Reagent	Delivered price [€/ton]	Dry price [€/ton]	Reaction based price [€/mole N]	Relative cost
Anhydrous ammonia	221	221	1.88	1.00
29.4 % aqua ammonia	99	337	2.86	1.52
Prill urea	199	199	2.99	1.59
70 % urea solution	153	218	3.28	1.74
50 % urea solution	141	282	4.24	2.25

These prices can only be regarded as rough reference values if no better data is available. Due to the fluctuation of gas prices and inflation, local circumstances including transportation costs, availability, demand and supply rate, taxes, etc., current local prices may deviate significantly (Himes 2004). The strong price fluctuation is supported by Cichanowicz (2010) who mentions a price of 400 $/ton of anhydrous ammonia, which is, after conversion to Euro, about 1.6 times the price of Himes (2004). Therefore, the important message of Table 4-12 is not the absolute prices but the price relation between the reagents.

The selected type of reagent influences not only the operating costs but also the initial investment due to different requirements regarding transportation, storage and handling of the chemicals (cf. e.g. Himes 2004; US EPA 2016). These differences, however, are comparably difficult to assess on single plant scale and the type of reagent is not always known at an early stage of investment planning. If data is available, it is recommended to consider the envisaged type of reagent in the selection of the specific investment reference value. However, there is no explicit methodological consideration of different investments for the reagents, as this would require detailed information about the reagent in use in the reference plant. This is often not the case, especially if publicly available reference data is to be used.

4.4.2.3 Electricity Cost

The electricity consumption of an SCR system consists of two major components. The first one is the direct consumption of the system for reagent storage, distribution and injection, control systems, etc. The second one is the energy demand to compensate for the pressure drop of the flue gas stream caused by the catalyst layers. This pressure drop needs to be compensated by additional fan power.

Based on the study of Fox (2011), US EPA (2016) states that the power consumption for operating a high-dust SCR is lower than for a low-dust SCR. The most important power consuming components are listed in Table 4-13. Their influence on the total consumption, however, varies significantly. Therefore, Fox (2011) compares the total power consumption of a high-dust and a low-dust SCR in a 440 MW coal-fired boiler. The power consumption for a low-dust unit is twice the consumption of the high-dust unit.

Table 4-13: Comparison of power consumption for high-dust and low-dust SCR installations (US EPA 2016).

Power component	High-dust SCR	Low-dust SCR
Induced draft fans	lower	higher (ca. 2x)
Ammonia system power	higher (ca. 20 %)	lower
Dilution air blower	higher (ca. 20 %)	lower
Dilution air heaters	higher (ca. 25 %)	lower
Ammonia pump	higher	lower
Seal air fans	same	same
Electrical & control power consumption	lower	higher (ca. 2x)
Total power consumption	lower	higher

The pressure drop caused by an SCR (Δp_{SCR}) is significantly influenced by the structure and surface of the catalyst. In addition to the pressure drop of each catalyst layer, the pressure drop of injection and mixing and the pipework contribute to the energy demand. The total pressure drop of an SCR is calculated by summing up the components mentioned above (cf. eq. (4-61), N^{layer} represents the total number of catalyst layers including spare layers if applicable).

The calculation of the annual electricity costs $\dot{C}_{el,SCR,a}$ is provided in equation (4-62). As the direct electricity consumption $P_{el,dir,SCR}$ depends only marginally on the load level, the total operating hours are applied in this case instead of the full load hours, in order to avoid an underestimation of the electricity demand. $W_{el,spec,pd}$ represents the specific energy demand of the pressure drop and c_{el} the price of electricity. Future projections of electricity prices can be derived from e.g. spot market price forecasts, as the electricity used for emission abatement within the power plant is no longer available for sale. Exemplary price projections are published regularly by e.g. the Energy Department of the European Commission (European Commission 2018).

$$\Delta p_{SCR} = \Delta p^{injection} + \Delta p^{piping} + \Delta p^{layer} \cdot N^{layer} \tag{4-61}$$

$$\dot{C}_{el,SCR,a} = \left(P_{el,dir,SCR} \cdot t_{op,a} + W_{el,spec,pd} \cdot \Delta p_{SCR} \cdot \dot{V}_{fg,a}^{wet}\right) \cdot c_{el} \tag{4-62}$$

Table 4-14 displays reference parameters for the calculation of the SCR pressure drop and the thereof resulting electricity consumption. These values shall be considered as reference values that may be customized by the user if data is available. No reference value is provided for the price of electricity due to its fluctuations and because it is comparably easy to obtain from public data for specific applications. A reference range for the total pressure drop is mentioned in Lecomte et al. (2017) with 5 mbar to 15 mbar.

Table 4-14: Reference values for pressure drop calculation (TFTEI 2015a; CAGI 2018).

Component	Symbol	Ref. value	Unit
Pressure drop injection	$\Delta p^{injection}$	1.5	mbar
Pressure drop piping	Δp^{piping}	2.5	mbar
Pressure drop layer	Δp^{layer}	1.5	mbar
Spec. energy demand of pressure drop	$W_{el,spec,pd}$	0.007	Wh/ (mbar*Nm³)

Regarding the direct electricity consumption of the SCR system ($P_{el,dir,SCR}$), very few reference values are available. EGTEI secretariat (2014) assumes a direct consumption of 0.01 MW. Even though the origin of this value is uncertain[32], it can be regarded as an acceptable reference value due to the comparably low influence of this parameter. According to Cichanowicz (2010), about 12 % of the total operating cost of an SCR (including fixed operating costs) is electricity cost. The major part thereof is needed to overcome the pressure drop.

Nalbandian (2006) offers a simple alternative to estimate an order of magnitude for the total electricity consumption of an SCR. She assumes the total plant electricity consumption to increase by about 0.6% after installing an SCR. Another alternative is provided by US EPA (2016). It calculates the direct electricity consumption and the electricity consumption to overcome the pressure drop via a factorial equation that, however, requires conversion to US units. This equation, as well as other factorial approaches in the US EPA methodology, is comparably nontransparent as there is no information about the background of the data, the main influences, actuality or applicability provided. It is therefore not mentioned in more detail in this work.

4.4.3 Fixed Operating Cost Calculation

The fixed operating costs of an SCR account for the operation and management costs of the system that occur independently of the operation time and mode. They are typically calculated as a percentage of the initial investment per year (Peters et al. 2003). Regarding the allocation of costs, various approaches exist and different regulations may apply.[33] Due to the aim of this work, which is the facilitation of investment calculation and not a precise accounting of costs, all sorts of fixed direct and indirect operation-related costs except capital costs are summarized in this category. In the case of economically non-profitable investments such as emission abatement installations, some 'conventional' cost items may be disregarded. Plant overhead, for

[32] It is most likely based on information of industry representatives in the TFTEI community.

[33] More details regarding cost classification and allocation are provided for example in Götze et al. (2015) and Friedl et al. (2013).

example, is usually not allocated to this type of investments (US EPA 2016). Insurance and taxes can also be omitted due to their small total amount (US EPA 2016). Therefore, administration costs are the only indirect costs that need to be considered. In order to facilitate the calculation approach, administration costs are integrated into the fixed operating cost calculation, as suggested by Cichanowicz (2010) and TFTEI (2015a).

$$\dot{C}_{op,fix,SCR,a} = I_{SCR} \cdot FOM \tag{4-63}$$

The calculation of the annual fixed operating costs $\dot{C}_{op,fix,SCR,a}$ in equation (4-63) takes a factor for operation and maintenance (*FOM*) into account that considers direct and indirect operation, maintenance and administration costs. It contains spare parts as well as labor. Some other approaches (e.g. Yelverton 2009) calculate labor separately, yet because of the low operational effort caused by SCR systems (US EPA 2016), the added value of this separation is considered low in comparison to the additional effort. If applicable (i.e. if sufficient data is available), the *FOM* can also consider contingencies in the context of operating costs, for example referring to fluctuations of energy, reagent and catalyst prices.

Reference values for the *FOM* are scarce, especially because many references do not clearly define the envisaged content of the factor. EGTEI secretariat (2014) calculates with a reference value of 2 % per year. The value mentioned in US EPA (2016) is 0.5 % per year, yet administrative expenditures are considered separately. In total, an amount of approximately 1 % per year results. Cichanowicz (2010) assumes a value of close to 1 % per year as well. Consequently, an FOM between 1 and 2 % per year seems reasonable for most applications.

For simplification, minor cost components such as auxiliary heat for the vaporization of water in the reagent solution (cf. Cichanowicz 2010; US EPA 2016) are not considered in this approach. It is therefore recommended rather to overestimate the *FOM* or to add a contingency in order to compensate these simplifications.

4.5 Selective Non-Catalytic Reduction (SNCR)

Due to the technological parallels between SCR and SNCR systems, the cost calculations of the two techniques have many similarities. Therefore, the following section on SNCR is less detailed and contains several references to the SCR chapter in order to avoid doublings. In general, SNCR systems are less complex and thus less cost-intensive than SCR systems. Therefore, fewer cost components need to be considered, the complexity of estimating these, however, is comparably high.

4.5.1 Investment Calculation

The investment calculation for SNCR is based on the same principle as for SCR. A specific investment value from a reference or existing plant needs to be defined and can be adopted for time, currency or capacity deviations. Reference values for the specific investment are provided in several publications. TFTEI (2015a) mentions an average reference value of 15.55 €/kW.[34] Reis (2010) lists fuel specific information for:

- Coal: 15 €/kW
- Oil: 15 €/kW
- Gas: 12 €/kW.

These values can be used if no better plant or company-specific data is available. Nalbandian (2006) confirms these values by providing a range of 10 to 20 $\$/kW_{el}$ for retrofits and 5 to 10 $\$/kW_{el}$ for new installations. The ICAC SNCR Committee (2008) also provides comparable values in the range of 5-15 $/kW.

[34] The validity of this number may be limited by the fact that only two installations were reported.

4.5.2 Variable Operating Cost Calculation

The variable operating cost calculation of SNCR systems is similar to the calculation for SCR systems excluding the catalyst, which is not needed for SNCR systems. Therefore, equation (4-44) is reduced by this component as displayed in equation (4-64). The calculation of the reagent and electricity cost is described in the following sections.

$$\dot{C}_{SNCR,op,var} = \dot{C}_{SNCR,reag} + \dot{C}_{SNCR,el} \quad (4\text{-}64)$$

4.5.2.1 Reagent Cost

The chemical processes and the thereof resulting equations for the reagent cost calculation are similar to those for SCR systems. Yet, in SNCR systems, the reagent is injected at significantly higher temperatures. This leads to a partial thermal deposition of the reagent, causing higher reagent consumption and thus higher stoichiometric ratios (IEA Clean Coal Centre 2017). To abate the same amount of NO_X in an SCR and an SNCR system, the SNCR requires two to three times more reagent than the SCR system (IEA Clean Coal Centre 2017).

Good process control is necessary to keep the ammonia slip below the threshold, as injection of reagent at lower temperatures or shorter than expected residence times directly increases the ammonia slip (IEA Clean Coal Centre 2017). Figure 4-2 displays exemplary stoichiometric ratios at different NO_X emission and reduction levels.

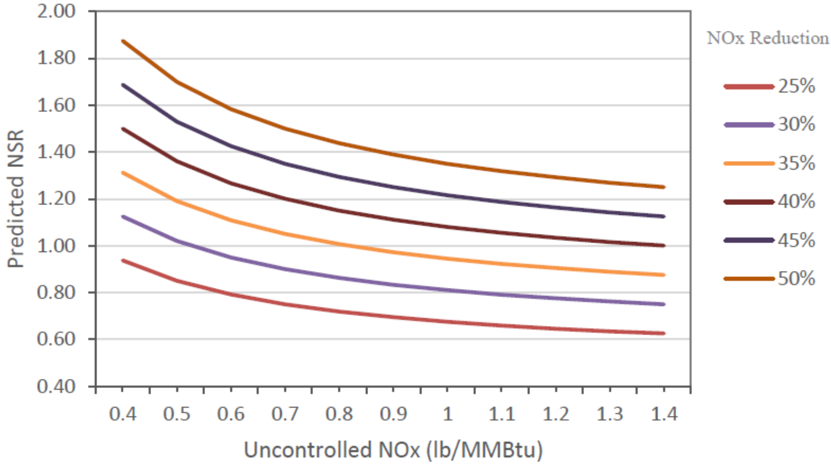

Figure 4-2: Course of stoichiometric ratios for urea in SNCR systems (NSR: Normalized Stoichiometric Ratio) (US EPA 2016).

4.5.2.2 Electricity Cost

In contrast to SCR, the pressure drop of an SNCR only results from the injection and mixing processes. Therefore, equation (4-61) can be reduced to one single component as displayed in equation (4-65).

$$\Delta p_{SNCR} = \Delta p^{injection} \tag{4-65}$$

$$\dot{C}_{SNCR,el,a} = \left(P_{el,dir,SNCR} \cdot t_{op,a} + W_{el,spec,pd} \cdot \Delta p_{SNCR} \cdot \dot{V}_{fg,a}^{wet}\right) \cdot c_{el} \tag{4-66}$$

Equation (4-66) displays the resulting calculation of the total electricity consumption. It consists of the same elements as the equation for SCR systems; yet, the energy consumption is significantly lower due to the less extensive technical setting. The reference values provided for injection, direct electricity consumption and specific energy demand of the pressure drop are assumed equal to SCR installations due to the lack of SNCR specific publicly available data. Nalbandian (2006) confirms the resulting order of magnitude by stating that the installation of an SNCR systems causes an increase of approximately 0.2 % of the total plant electricity consumption (compared to 0.6 % for SCR systems).

4.5.3 Fixed Operating Cost Calculation

The calculation of fixed operating costs is similar for SCR and SNCR systems and has been provided in chapter 4.4.3. As no deviating reference values for SNCR systems have been identified, the same order of magnitude (about 1-2 % of the initial investment per year) is assumed for SNCR systems. The lower total investment automatically considers fewer administrative and operational work, due to the missing catalyst, as the fixed operating costs are calculated as a percentage of the total investment.

4.6 Total Cost and Abatement Efficiency

The consolidation of all cost items is methodologically identical for both SCR, and SNCR systems. It is therefore summarized in the following chapter and can be applied identically for both technologies. The first part of the chapter describes the (possible) consideration of contingencies in the given context. Thereafter, a cost summary is derived including a comparison of the typical cost structures of SCR and SNCR. Finally, the total emission abatement calculation is provided. Combining the cost assessment and the emission calculation, the cost-efficiency of the investment project can be derived.

4.6.1 Contingencies

Some references such as Himes (2004) recommend the consideration of contingencies in the given context. These contingencies account for possible mistakes and difficulties during the planning and construction phase as well as for external influences such as unexpected weather events or price developments that cause additional costs (Chauvel et al. 2003). Himes (2004) recommends 15 % process and 15 % project contingency for comparable applications. These amounts suit the study-level accuracy of +/- 30 % as mentioned before (Geldermann 2014). The goal of considering contingencies is to avoid underestimating the budget and cost calculation. Therefore, it is explicitly relevant for risk-averse deciders, as budget overestimations are usually less critical than underestimations and underestimations are far more common (Vose 2015; van der Slot et al. 2015).

4.6.2 Cost Structure and Summary

The total investment and cost calculation for NO_X abatement in large combustion plants can be summarized in three main categories. The initial investment, the fixed annual operating costs and the variable operating costs. The initial investment has been discussed in detail in chapters 4.3, 4.4.1 and 4.5.1. The fixed operating costs (chapters 4.4.3 and 4.5.3) are derived on an annual base and calculated as a percentage of the initial investment. The variable operating costs are calculated based on the output (i.e. the operating scheme) of the plant and provided in either Euro per MWh or Euro per year. They consider the consumption of catalyst (only in case of SCR), reagent and energy. Contingencies can be added to individual (particularly uncertain) cost items or to the comprehensive cost components.

The total costs of secondary emission abatement installations vary a lot depending on the specific plant and technology. In general, they play a considerable role in the cost structure of a plant. According to Nalbandian (2006), about 8 % of the total production costs in a fully depreciated coal power plant are caused by the costs of an SCR.

A broadly valid comparison between the annualized investment and the total operating costs of emission control installations is difficult due to the major influence of the depreciation time and the operating scheme of the plant.

Heide (2012a) states that about 15 to 25 % of the total annual costs of typical SNCR installations are caused by the investment annuity based on a lifetime of 15 years. This data comes from waste combustion plants, but the value of 25 % is confirmed by ICAC SNCR Committee (2008) as well. SCR installations cause higher total annual costs[35] with a higher share of the investment annuity (about 40 % of the total annual costs), as investment expenditures are significantly higher for SCR systems (Heide 2012a).

As mentioned above, the cost components are not directly comparable due to the differences in time of occurrence and dependency of operating schemes. Many economic methods exist to merge the cost components to one overall project value. Some examples have been introduced in chapter 3.4 and one concept, the annuity method, will be explained in the next section in order to derive the emission abatement efficiency.

The aim of this work, however, is to investigate investment decision-making in more detail using a real option approach. Therefore, the results of the calculation methodology presented above (the individual cost components) will directly serve as input parameters for the second part of the model described in chapter 5.

4.6.3 Total Emission Abatement and Abatement Efficiency

For calculating the costs of air pollution equipment at an annual level, the costs of the initial investment and the capital cost throughout the lifetime need to be annualized using the annuity method. Therefore, the capital recovery factor (*CRF*) according to the annuity method described in 3.4.2 is used (Marlowe et al. 1999; Schnelle et al. 2016). The annualized capital cost

[35] In the examples of Heide (2012a) the total annual costs of an SCR are three to five times higher than those of an SNCR.

$\dot{C}_{cap,a}$ are calculated according to equation (4-67) as the sum of all investment expenditures (for primary and secondary measures, if applicable) with *r* representing the interest rate and *L* the (average) equipment lifetime.

$$\dot{C}_{cap,a} = \sum C_{inv} \cdot CRF = \sum C_{inv} \cdot \frac{r \cdot (1+r)^L}{(1+r)^L - 1} \tag{4-67}$$

The total annual costs consist of the annualized capital costs and the annual variable and fix operating costs as shown in equation (4-68). It shall be mentioned that this approach does not incur a discounting of future operating costs. Therefore, a quantitative comparison with other investment evaluation methods such as the net present value may deliver minor deviations regarding the results. Within the accuracy of this study level approach, the deviations are, however, acceptable in favor of increasing transparency and simplification of the calculations.

$$\dot{C}_{tot,a} = \dot{C}_{cap,a} + \dot{C}_{op,var,a} + \dot{C}_{op,fix,a} \tag{4-68}$$

Regarding the interest rate *r* to be applied in equation (4-67) controversial debates and intensive research are going on (cf. Götze 2008; Götze et al. 2015; Hering 2008; Hull 2012; Ross 2011). A more detailed discussion of the applicable interest rate in the given context will follow in chapter 5.

The calculation of the specific abatement cost per mass of NO_X abated is displayed in equation (4-69). This value is an important parameter for the techno-economic comparison of alternative technologies.

$$C_{tot,spec}\left[\frac{€}{kg_{NOx\ abated}}\right] = \frac{\dot{C}_{tot}\left[\frac{€}{a}\right]}{\dot{m}_{NOx\ abated,a}\left[\frac{kg}{a}\right]} \tag{4-69}$$

4.6.4 Cross-Media Induced Costs

The most relevant cross-media effects for NO_X abatement were introduced in section 2.2.6. As discussed in this section, hardly any systemic effects exist that cannot be controlled by technical or operational measures. Furthermore, many of these effects are difficult to quantify from an economic perspective, without knowing plant-specific details.

Therefore, the only cross-media effect that shall be considered in one of the case studies of chapter 6 is increasing CO_2 emissions caused by additional electricity consumption. These can be quantified by emission factors and rated with the prices of e.g. CO_2 certificates or taxes.

Table 4-15 provides reference emission factors for several fuels based on data published by the German Federal Environmental Agency. The values might deviate for plants in other parts of the world, as e.g. the origin and preparation of fuels may be different. For order of magnitude contemplations, however, these values can be used as reasonable estimates.

Table 4-15: Fuel specific emission factors for the German atmospheric emission reporting for 2016 (Umweltbundesamt 2018).

Type of fuel	Emission factor	Unit
Hard coal	93.6	t_{CO2}/TJ
Lignite	98.0-113.0	t_{CO2}/TJ
Crude oil	73.3	t_{CO2}/TJ
Natural gas	55.9	t_{CO2}/TJ
Wood residues	107.8	t_{CO2}/TJ
Biogas	90.6	t_{CO2}/TJ

From the additional electricity consumption caused by emission abatement measures $\Delta W_{el,a}$ (both primary and secondary measures can be considered), the emission factor $f_{emission}$ and the price of CO_2 emissions c_{CO2}, the annual additional costs $\dot{C}_{CO2,\mathrm{a}}$ can be calculated according to equation (4-70). The conversion rate from TJ in MWh is 278.

$$\dot{C}_{CO2,\mathrm{a}} = \frac{\Delta W_{el,a}}{\eta^{net}} \cdot f^{emission} \cdot c_{CO2} \tag{4-70}$$

This additional cost item can be considered if national policy implies to do so (i.e. if a CO_2 pricing scheme is in force). Its designation depends on the type of policy instrument in force, yet in most cases, it can be considered a variable operating cost item. The prices for CO_2 also depend primarily on the type of policy instrument in use. Providing reference data for some parts of the world might be misleading here, as other regions may face greatly deviating prices. As these prices are based on policy programs, however, it can be expected that the corresponding information is publicly available for the given region. An exemplary case considering CO_2 emission fees will be assessed in section 6.5.2.

4.7 Discussion and Validation of Results

The results of the calculation methodology presented above can be validated in two different ways. The results can be analyzed and compared with the results of other studies and calculation tools. Exemplary tools are the cost curves developed by Vijay et al. (2010) or the Coal Utility Environmental Cost (CUECost) tool developed by the US EPA (Yelverton 2009). The cost calculation methodology provided by the US EPA (2016) lists further reference values and calculation examples. Reference values for (specific) investments have already been mentioned in the corresponding chapters 4.4.1 and 4.5.1. More cost values and references are also mentioned in Nalbandian (2006). However, the comparison of results remains difficult due to the complexity of the tools with a broad variety of input data and assumptions. Therefore, it is impossible to calculate one case study in two or more tools using exactly the same input data, as every tool requires different input data.

Consequently, a detailed comparison can only be made with realistic plant data, as (only) plant operators possess the entire data set that is necessary as input for the different tools. Publicly available data is never detailed enough for precise case studies; a validation from a scientific point of view is hence rather difficult. During the project work of TFTEI, however, it was possible to cooperate with plant operators. They did not provide their full data sets but used the TFTEI methodology, which is closely related to the methodology described above, with their data. Satisfying results that met the expectations of study level accuracy were reported.

The methodology provided above aims at study level accuracy (+/- 30 %). Therefore, some process details have been neglected in favor of simplicity and transparency. Examples are:

- Unburned carbon change
- Excess air change
- Ash disposal
- Reagent tank size
- Altitude of the plant.

Miller (2011) and US EPA (2016) describe and consider some of these aspects, yet their influence on the final results is (for most existing plants) very low. Furthermore, startup and shutdown, as well as part load operation are not considered in the methodology. As described in 2.1.3 the influence of the operating strategy of a plant on the emission abatement results and costs may be significant. It is, however, very complex to integrate operating strategies in a generally valid manner due to their technical complexity. Therefore, this aspect shall be regarded as an area of future research. Sloss (2016) provides an overview of flexibility costs for coal-fired plants, but without focusing on emission abatement effects.

In general, if the user of the methodology is aware of a significant deviation between the site-specific conditions and the industry standard (which is considered in the reference values of the methodology), this deviation should be evaluated with regard to its effect on investment and operating costs in order to avoid major falsifications of the results.

4.8 Transferability of the Methodology

The calculation methodology has been developed for NO_X abatement installations in large combustion plants. The transferability to other sectors or pollutants depends on the specific application. For NO_X abatement in other sectors with large industrial plants, it can be comparably easy to transfer the methodology. For other sectors or pollutants, it may be a lot more difficult.

Even among large combustion plants for energy generation, major deviations with regard to cost calculation may occur. These deviations can be caused by differing installation engineering, heterogeneous fuels, different locations and other conditions such as the complexity of retrofits. A site-specific plausibility check for all assumed values is hence recommended.

Other sectors, for example the waste processing sector (waste incineration plants) or the cement industry use very similar techniques for NO_X abatement. For such applications, specific parameters may have to be adapted, e.g. the catalyst parameters may be influenced by increased catalyst poisoning (cf. e.g. Richers and Günther 2014).

NO_X abatement systems for mobile sources such as cars or trucks are based on identical technical principles, nevertheless, the design and size of the systems are completely different from stationary industrial applications. The cost calculation methodology at hand will hardly be of use for these applications.

For other pollutants in large industrial plants, some parts of the methodology may be of use, such as the calculation of the flue gas volume. The calculation of electricity costs may also be adopted, even though the factors for pressure drop and direct consumption are certainly to be adapted. Other aspects such as the calculation of the initial investment depend primarily on the abatement technology and have to be adapted for other pollutants. Examples of investment and cost calculation for PM and SO_2 are provided in TFTEI (2015a) and US EPA (2016).

For the second part of the modeling approach in the following chapter 5, all sorts of abatement techniques can be used, as long as all relevant cost components (annual costs, investment, fixed and variable operating costs) are available.

5 Model Part 2: Option-Based Decision-Making (ROA)

Based on the theoretical introduction in chapter 3 and the outputs of the techno-economic model in chapter 4, the decision-support model will be introduced in the following. The chapter starts with a definition of the basic terms and assumptions and a description of the interface with the techno-economic model, followed by an overview of constraints and input values. Furthermore, two possible calculation perspectives will be introduced with regard to their idea and mathematical implementation. A first set of stylized examples will also be analyzed in order to demonstrate the general behavior and possible results of the model. Finally, both perspectives will be compared to each other and assessed for their deviations, strengths, and weaknesses. [1]

5.1 Definitions, Assumptions and Input Data

Some important definitions and assumptions need to be clarified, as the underlying application of legally enforced environmental investments includes several deviations from financial options and common real option applications. Therefore, this section can also serve as reference for the understanding of the further calculations and results of this work. For other types of investment projects, the methodology and the outcomes might be applicable as well, yet it needs to be investigated in detail, to which extent the assumptions and definitions in this study apply accordingly in order to assess the transferability of results and methodological constraints.

[1] Parts of this chapter have previously been published in Mayer and Schultmann (2017) and Schiel et al. (2019).

5.1.1 Application Specific Terms and Definitions

Based on the nomenclature of financial option valuation, the most important terms will be briefly introduced in the context of the application at hand in the following. This assessment reveals several deviations from ‘standard’ option valuation literature and is therefore of great importance for the further understanding and discussion of the ROA model and its results.

5.1.1.1 Project

The emission control investment and its operation throughout the lifetime are defined as project in the following. Therefore, all directly related cash flows will be considered, no matter if it is a retrofit in an existing plant or a new installation. Other cash flows related to e.g. the operation of the plant itself will not be considered in the context of this work, as discussed in 3.6. This delimitation can be regarded as system boundary for the calculation of all project related cost components in order to derive the NPV of the project.

5.1.1.2 Option

The option in the considered context differs from other (real) option applications, as the valued option is not defined as the option to invest, but to advance the investment compared to the latest considered decision-making time. It is therefore assumed that the investment has to be executed by the end of the decision-making period; not to invest, is not allowed in this model.

One consequence resulting thereof is the need for a rolling horizon planning. As the investment needs to be executed by the end of the decision-making period, it is not possible to predefine a fixed investment threshold. Instead, it needs to be assessed in every period whether an immediate investment is advantageous compared to a delayed investment. If the investment is delayed, the same analysis needs to be conducted again in the subsequent period, based on the actual development of the uncertain parameters.

5.1.1.3 Strike Price

The strike price is defined as the NPV of the project at the considered time *t*. By considering the NPV as strike price and not e.g. the total investment, all sorts of uncertainties and policy instruments with monetary outcomes can be investigated, such as fees and taxes, subsidy systems, commodity prices and the like. In order to compare the value of the project at different times in the future, the simulated strike prices, i.e. the NPV at those times, can be compared. This will be explained in further detail in 5.2.2 and 5.3.2. In order to support the intuitive understanding of the calculations, the strike price will be denoted as NPV in the following.

5.1.1.4 Option Price

As the definition of the option differs from common (real) option applications, the definition of the option price differs as well. In a financial context, the option price has to be paid at the beginning of the lifetime of the option, no matter if it will be executed later or not. In the application at hand, the option price is defined as the additional cost that occurs when advancing the investment, i.e. when executing the option. Therefore, the option price is an imputed cost item that is considered for decision-making without causing any expenditures if the option is not executed.

In this work, the imputed interest is selected as a suitable measure for the option price. However, if a considered investment is known to cause higher or lower costs when being delayed, this value may be adjusted. The use of the imputed interest as option price may be questioned, as one could state that the investment needs to be executed in any case. Therefore, it might be sufficient to use only the difference between the present and the future value of the imputed interests as the option price (i.e. the discounted imputed interest).

Particularly for risk-averse decision-makers, however, this might be an excessively optimistic approach. Future research with regard to the precise definition of the option price is hence recommended at this stage with regard to both the base value considered (i.e. the imputed interest in this case) as well as the applicable interest rate.

5.1.1.5 Real Option Value

The real option value ROV is defined as the intrinsic value of the option. It refers to the difference between the current price of the underlying asset and the strike price of the option (cf. e.g. Carr and Jarrow 1990). In the given context, the current price is the NPV in t_0 and the strike price is the discounted NPV in the considered future period t. The resulting difference is reduced by the option price in order to calculate the option value. If the option value is positive, the option to advance the investment is in the money, if it is negative, it is set to zero and the option is out of the money.

5.1.1.6 Return

In order to evaluate the investment decision, it is necessary to compare the resulting option value with an expected return R. Due to the consideration of the intrinsic option value and the fact that option values can never be negative, it is sufficient for a Monte-Carlo-Simulation to have one path in the money in order to have a positive total option value. Therefore, it is not sufficient to have an option value above zero but a distinct return has to be defined as threshold value. A reasonable recommendation for environmental investments could be the long-term investment rate as further discussed in section 5.1.5. This is, however, not a fixed default value but may be adapted according to the expectations and risk perception of the decision-maker.

In this work, R is calculated as the ROV divided by the investment at time t_0. This can be questioned, as the investment does not gain revenues but causes costs throughout its lifetime. Therefore, the NPV could also be used as base value instead of the investment. However, as the question is not if to invest, but when to invest, the costs over the lifetime can be argued to occur anyway, no matter when the investment will take place. Therefore, the investment is selected as reference value, as this enables a comparison between the achieved return and the imputed interest, which is also calculated as a factor of the total investment.

5.1.2 Interface with Techno-Economic Model

The interface with the techno-economic model described in chapter 4 is one-directional, i.e. the techno-economic model delivers data for the ROA model but not the other way round. Table 5-1 provides an overview of the output parameters that serve as input for the ROA. These will be complemented by direct input values for the ROA model.

Table 5-1: Data from the techno-economic model to be considered for the ROA.

Data from techno-economic model	Parameters	Unit
Investment	Total (initial) investment	€
Operating costs		
Energy	Consumption	MWh/a
	Price	€/kWh
Reagent	Consumption	t/a
	Price	€/t
Catalyst	Volume	m³
	Lifetime	h
	Price	€/m³
Operation and management	Factor	% of TCI/a
Emissions		
Emissions without abatement	Total emissions	t/a
Emissions with abatement	Total emissions	t/a
Timeframe		
Lifetime (control technique)	Lifetime of the investment	a
Operating time (plant)	Plant operating hours	h/a

The level of detail of the parameters can be adapted according to the needs of the scenarios. If, for example, the operating costs are considered as fixed, a total summed-up cost is sufficient. Yet, in order to be able to investigate different parameters with regard to their decision relevance, a higher level of detail with individual cost components such as reagent, catalyst, etc. needs to be considered.

5.1.3 Time Constraints

In case of a delayed investment, the lifetime of the investment is not clearly predefined. Two alternatives are possible, that are visualized in Figure 5-1. The decision-making period, i.e. the time between the current time t_0 and T is typically a period of not more than 5 years, because predictions beyond this point, especially in a political context, are very uncertain and usually not possible/reasonable.

The economic lifetime L of the investment, however, is typically much longer (about 15 to 30 years in case of emission abatement installations), depending on the technical lifetime of the installation and the lifetime of the overall plant.[2] While delaying the initial investment, the end of the lifetime can either be delayed as well, which results in a fixed lifetime L and a variable end of the considered time frame t_L (cf. 'Fixed lifetime' in Figure 5-1). This is particularly reasonable if the plant is expected to be operated longer than the economic lifetime of the environmental investment. If, on the other hand, the operating time of the plant is limited (e.g. due to permit limitations), the lifetime of the investment may be shortened by delaying the investment (cf. 'Fixed end of life'). The more suitable contemplation has to be selected for every application depending on the given circumstances.

[2] The remaining lifetime of the plant is particularly relevant in case of retrofits.

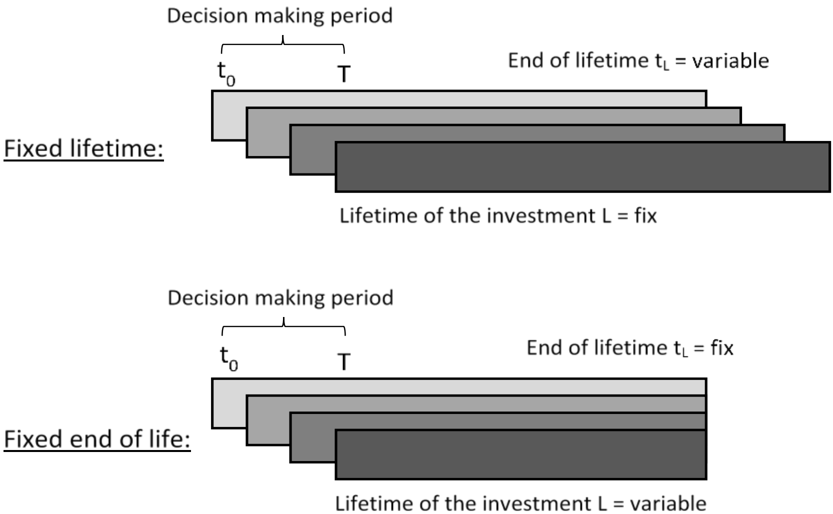

Figure 5-1: Alternative considerations of the project lifetime in case of a delayed investment .

5.1.4 Stochastic Processes and Jumps

Based on the discussion in 3.5.4 and 3.6.2, Geometric Brownian Motion and Markov Jumps are considered the most interesting stochastic processes with regard to the considered applications. Therefore, they will be used for the simulations in the case studies of chapter 6. For the examples in this chapter, there is no explicit stochastic process defined but stylized trends and developments are assumed. These courses of investments do not represent any realistic scenarios but aim at supporting the intuitive understanding of the methodology.

5.1.5 Interest Rate

The calculations in the following are based on the present value approach. Therefore, the interest rate is an important influencing parameter, as all future cash flows are to be discounted. The selection of an appropriate interest rate is especially critical for long-term investments with environmental relevance. According to the German agency for environmental affairs it is recommended to use the long-term investment rate for low-risk bonds (Umweltbundesamt 2012). Disregarding short-term fluctuations, this rate tended to level off at around 3 % during the last 150 years (Umweltbundesamt 2012). Even in times of very low interest rates, this rate is expected to be lower than usual expectations regarding the return on investments in industrial plants. As the primary aim of environmental investments is not to gain revenues, the recommended 3 % interest rate will be used in the following, although not all companies might share this opinion.

Higher interest rates tend to overestimate the time value of money, which leads to a disproportional preference for later investments. In this work, the cost of capital is not assessed in detail, i.e. equity and outside capital is not distinguished for simplicity reasons. If the precise situation of a company is known, however, the WACC (Weighted Average Cost of Capital) could be used in order to differentiate appropriately.

5.1.6 Input Data for Stylized Examples

Five stylized examples will be used in the following, in order to visualize the implementation and the behavior of the methodology in typical scenarios and to explain the calculations in more detail. These examples are based on a NO_X abatement installation in a 1 000 MW coal-fired combustion plant. The costs are calculated according to the methodology described in chapter 4. The initial state of the examples is hence based on a realistic setting.[3] This is not the case for the assumed developments of the *NPV* for investments between t_1 and T in the five examples. These development paths of the *NPV* are not intended to display actual future developments but represent five different contrasting settings.

[3] The initial state is the current value (NPV) of the project in t_0.

All exemplary paths assume an initial investment at time t_0 of 20 M€. The system has a lifetime of 20 years and annual operating costs of 1.5 M€ accrue. The operating costs are assumed to remain constant throughout the lifetime and emission fees are not considered in favor of transparency.[4] Regarding the lifetime, the 'fixed lifetime' contemplation is assumed. The decision-making period spans five years, starting from t_0 with a latest possible investment in t_4. The interest rate is set to 3 %.

Table 5-2 displays the underlying data for the stylized examples. The net present value of the total operating costs (NPV_{C_{op},t_0}) over the lifetime of the investment is calculated in equation (5-1). Starting from the considered investment time t the annual operating costs OC_{annual} are discounted to t_0.[5]

$$NPV_{C_{op},t_0} = \sum_{k=t}^{L+t} \dot{C}_{op,a} \cdot (1+r)^{-k} \tag{5-1}$$

Table 5-2: NPV of the operating costs over the lifetime and investment examples in M€.

t	$NPV_{Cop,t0}$	Investment scenario				
		1	2	3	4	5
0	22.99	20	20	20	20	20
1	22.32	20	19	23	30	30
2	21.67	20	18	26	30	20
3	21.04	20	17	29	30	30
4	20.42	20	16	32	30	25

4 These assumptions may be questionable in practical applications, yet they facilitate the reproduction of the calculations.

5 *t* is the time of the considered execution of the investment. As the decision-making focusses on the current period t_0 (the question is whether to invest now or to delay the investment), all operating costs are discounted to t_0, even though the investment may be executed later and operating costs do not occur prior to *t*. This contemplation will be helpful for the subsequent calculations.

As described above, the operating costs are assumed to remain constant over time and are thus independent of the investment scenarios. The investment is hence considered the only uncertain variable in the following. The five stylized investment examples are designed to follow different trends (steady investment, decreasing investment, increasing investment, investment jump, fluctuating investment). This data will be used for the exemplary calculations of the two perspectives in sections 5.2.4 and 5.3.4.

5.2 Savings Perspective

As introduced already, the calculations in the following are based on a twofold contemplation with two perspectives that result from the politically enforced must-investment. The advancing of an investment may gain savings compared to a future investment with uncertain NPV. It is also possible, that the delay of an investment causes losses, again if the NPV increases significantly in the future. The main difference between the two perspectives is the angle of view. Both perspectives will be introduced in the following, starting with the savings perspective in this section.

In most cases, the results of both perspectives are, as intuitively assumed, identical. Nevertheless, deviations may occur in certain cases. The description of the idea and aims of the savings perspective is followed by detailed explanations of its mathematical implementation. In order to assess the calculations and their results in more detail, the results of the five stylized examples will finally be introduced and discussed.

5.2.1 Idea and Setting

As introduced above, the savings perspective investigates the savings of an advanced investment compared to a later investment. The savings hence represent a reduction of the total economic losses caused by the project, as the calculations are based on the assumption that the considered investments are economically disadvantageous.

The mathematical basis of the savings perspective is dynamic programming with its backward induction approach. Starting from the end of the decision-making period (*T*), it compares the project value of an investment in *T* with the project value of an investment in *T-1*. The project value is calculated as the NPV of the project. It includes the initial investment and all future cash flows *CF* throughout the lifetime *L*, discounted to the considered time *t* with the interest rate *r*. In the following, *NPV* is exclusively used for the overall NPV of the project and thus not further indexed. A residual value at the end of the lifetime is not considered. The total decision-making period is allocated to a discrete number of decision-making times t_i with $i \in \{0, 1, 2, \ldots, T\text{-}1\}$.[6] Each t_i represents the start of one period (e.g. one year) and all costs are allocated to the beginning of the corresponding period.

5.2.2 Mathematical Implementation

Equation (5-2) displays the calculation of the *NPV* for each t_i if no emission fees (*NEF*) are considered.[7] The investment is by definition an expenditure, whereas the accumulated cash flows are in this case also (mostly) expenditures and thus negative values. In order to facilitate the subsequent calculations, the (negative) cash flows are subtracted from the (positive) investment, in order to get a positive NPV.[8] Consequently, it needs to be kept in mind that a low NPV is economically advantageous in this case, as it contains lower total expenditures.

[6] Because the counting of periods starts at time 0, the enumeration ends at *T*-1 in order to have the correct number of time steps.

[7] Emission fees, if applicable, are induced by policy instruments such as taxes and trading schemes.

[8] In fact, the absolute values of the investment and the cash flows are summed up.

Equation (5-3) is an extension of (5-2) including the consideration of emission fees (*EF*). All annual costs are discounted to the considered time *t*, whether they occur before or after *t*. If *EF* are considered, cash flows prior to *t* (which are typically caused by fees on pollutants emitted before the installation of an abatement system) are also taken into account in order to calculate the *NPV* of the project. This is necessary, as these expenditures are directly influenced by delayed investment decisions. Equation (5-3) displays a 'fixed lifetime' contemplation (cf. section 5.1.3), therefore, the total number of time steps increases if the investment is delayed.[9] If emission fees shall be considered in a 'fixed end of life' setting, the upper bound of the summation has to be reduced by the index of the considered investment period *t*.[10]

$$NPV_{t,NEF} = I_t - \sum_{k=0}^{L-1} (CF_{t+k} \cdot (1+r)^{-k}) \tag{5-2}$$

$$NPV_{t,EF} = I_t - \sum_{k=-t}^{L-1} ((EF_{t+k} + CF_{t+k}) \cdot (1+r)^{-k}) \tag{5-3}$$

Due to the mandatory investment constraint, the investment needs to be executed in *T* at the latest. In order to calculate the investment strategy for *T-1*, the *NPV* of an investment in *T* and *T-1* are to be compared. Therefore, the option price *OP* (cf. eq. (5-4)), which consists of the imputed interest caused by the investment, is added to the *NPV*. If the *NPV* in *T* discounted to *T-1* is lower than the *NPV* in *T-1* plus the *OP* from *T* to *T-1*, an investment in *T* should be favored. Otherwise, the investment is recommended to be advanced to *T-1* (cf. eq. (5-5) and (5-6)).

$$OP_{T-1} = I_{T-1} \cdot r \tag{5-4}$$

9 Reinvestments could be considered in order to create periods of the same length. However, this appears highly uncertain in such a volatile environment with comparably long lifetimes of investments. Therefore, reinvestments will not be considered in the following.

10 Assuming that *L* represents the total considered lifetime of the installation starting from t_0.

$$NPV_{T-1} + OP_{T-1} < NPV_T \cdot \frac{1}{1+r} \rightarrow Favor\ investment\ in\ T-1 \tag{5-5}$$

$$NPV_{T-1} + OP_{T-1} > NPV_T \cdot \frac{1}{1+r} \rightarrow Favor\ Investment\ in\ T \tag{5-6}$$

The procedure for the preceding period *T-2* is similar to the steps described above, but the *NPV* of the current period needs to be compared to the *NPV* of the favored succeeding period $t*$. Therefore, the general versions of equations (5-5) and (5-6) are displayed in (5-8) and (5-9), with the favored succeeding period considered.[11]

$$OP_t = \sum_{k=1}^{t^*-t} I_t \cdot r \cdot \frac{L+1-k}{L} \tag{5-7}$$

$$NPV_t + OP_t < NPV_{t^*} \cdot \frac{1}{(1+r)^{(t^*-t)}} \rightarrow Favor\ investment\ in\ t \tag{5-8}$$

$$NPV_t + OP_t > NPV_{t^*} \cdot \frac{1}{(1+r)^{(t^*-t)}} \rightarrow Favor\ investment\ in\ t^* \tag{5-9}$$

If in *T-1* an investment in *T* was favored, the *OP* for *T-2* needs to be calculated from *T* to *T-2*. If more periods are to be considered, the *OP* needs to be calculated for the number of periods between *t* and the favored succeeding period *t**. Equation (5-7) displays the calculation of the *OP* for an arbitrary number of periods between the current period and the favored succeeding period $t*$. This calculation assumes linear depreciation throughout the lifetime *L* of the investment and an annual aggregation of interests without discounting the imputed interests of future periods. These assumptions simplify the actual situation, yet, the error caused by these simplifications is considered acceptable.

[11] *t** needs to succeed *t*, therefore *t* > t.* The initial *t*=T* and the initial *t=T-1.*

The procedure described above is executed from T to t_0 for every price path generated by Monte-Carlo-Simulation according to the underlying stochastic process. To derive an overall option value, every path that recommends an investment later than in t_0 is set to 0 (cf. (5-10)), as the option to advance the investment to t_0 is out of the money in these paths. For all other paths, the real option value is defined as the savings that occur by advancing the investment compared to the next best time t^*. $ROV_{t_0,mc,s}$ represents the option value of the Monte-Carlo path *mc* in the savings perspective *s*.

$$ROV_{t_0,mc,s} = \\ = \begin{cases} 0 & if \quad \frac{NPV_{t^*}}{(1+r)^{t^*}} < NPV_{t_0} + OP_{t_0,t^*} \\ \frac{NPV_{t^*}}{(1+r)^{t^*}} - (NPV_{t_0} + OP_{t_0,t^*}) & if \quad \frac{NPV_{t^*}}{(1+r)^{t^*}} > NPV_{t_0} + OP_{t_0,t^*} \end{cases} \tag{5-10}$$

In the savings perspective, the real option value is a true value, as it represents the expected value of the savings that result from an advanced investment. A maximization of the real option value *ROV* is thus economically advantageous. The overall real option value for the maximum savings scenario ROV_S is calculated as the mean of the results of all Monte-Carlo simulated paths (cf. eq. (5-11)).

$$ROV_s = \frac{1}{MC} \cdot \sum_{mc=1}^{MC} ROV_{t_0,mc,s} \tag{5-11}$$

The resulting real option value is positive as soon as one path recommends an immediate investment. Therefore, it is not sufficient to have a positive *ROV* but a certain threshold needs to be defined that has to be met in order to recommend an immediate investment. There is no predefined threshold value for such applications in literature but a certain expected return on investment has to be defined by the decision-maker. This expected return *R* could be equal to the interest rate *r* as the focus of the considered type of investments is not to achieve revenues. A return of e.g. 3 % could serve as a contingency for future risks. Comparing the overall real option value ROV_S with R, the investment strategy for the maximum savings perspective can be derived (cf. eq. (5-12)).

$$\begin{matrix} invest\ in\ t_0 & if & ROV_s > R_s \\ delay & if & ROV_s < R_s \end{matrix} \tag{5-12}$$

If the real option value ROV_S is higher than R, it is recommended to invest in t_0. If the real option value is lower than R, a delay of the investment is to be favored. Based on new information, the model can then be recalculated in the next period according to the rolling horizon approach.

5.2.3 Further Contemplations

To support the decision-making with additional information, not only the average real option value in comparison to the expected return can be considered, but also the share of paths in the money may be of interest. Particularly in the case of a very volatile situation with a small number of paths with very high savings, the average real option value as single decision-making criterion may lead to questionable decisions.

The final decision-making may also be influenced by the risk perception of the decision-making board. Decision theory rules may support a reasonable decision-making based on the applicable circumstances. More detailed references are provided in 3.4.4 and further discussions will follow in the case studies of chapter 6.

5.2.4 Stylized Examples

The results of the maximum savings perspective for the stylized examples introduced above are displayed in Table 5-3. Example 1 assumes no changes in the investment sum over the considered decision-making period. Thus, no matter at what time the investment is executed, investment expenditures are always 20 M€. Thereof, the NPV of the whole project (investment plus operating expenditures) is calculated and discounted to the considered period t (NPV_t) and the current period t_0 (NPV_{t_0}). The option prices *OP* for advanced investments are also displayed for all combinations of considered time and (next best) investment time.[12]

The calculations of the real option values (*ROV*) start for every example from the bottom (t=T=t_4). In example 1, the calculated *ROV* of an advanced investment in period 3 (compared to period 4) is -1.9 M€, i.e. the advanced investment would lead to a loss and the resulting *ROV* for this period is thus 0. Therefore, the favored investment period for period 3 (t_3^*) is t_4. The preceding period t_2 is thus compared to t_4 and again the calculated *ROV* is negative (-3.6 M€), the resulting *ROV* is thus 0. Hence, the investment is recommended in t_4, t_2^* is also t_4. The same steps follow for periods 1 and 0 with an overall result that recommends an investment in t_4. The calculated *ROV* for t_0 is -7.0 M€, which means that the resulting *ROV* for the whole example is 0. In this case, an advanced investment does not lead to savings, the option is not in the money and consequently, the option to advance the investment should not be exercised. This result meets the expectations, as equal investment expenditures in all considered periods with constant operating expenses throughout the lifetime do not justify an advanced investment from an economic point of view due to the time value of money.

The calculations for the second example are similar to the first one and the result again supports the intuitive assumption. Due to the declining total investment, an advanced investment is even less reasonable than in example 1, the real option value is 0 again. This example represents a situation with declining investment expenses caused by technological developments, economies of scale or learning curve effects.

---

[12] The *OP* in Table 5-3 are calculated and displayed from time τ_1 to τ_2, with τ_1 displayed in the columns and τ_2 in the lines.

Table 5-3: Maximum savings results of the stylized investment examples [M€].

t	I	NPV_t	NPV_{t_0}	OP				ROV	t_{inv}	t*
				t_0	t_1	t_2	t_3			
Example 1								0	t_4	t_4
0	20.0	43.0	43.0					0	t_4	t_4
1	20.0	43.0	41.7	0.6				0	t_4	t_4
2	20.0	43.0	40.5	1.2	0.6			0	t_4	t_4
3	20.0	43.0	39.3	1.7	1.2	0.6		0	t_4	t_4
4	20.0	43.0	38.2	2.2	1.7	1.2	0.6			
Example 2								0	t_4	t_4
0	20.0	43.0	43.0					0	t_4	t_4
1	19.0	42.0	40.8	0.6				0	t_4	t_4
2	18.0	41.0	38.6	1.2	0.6			0	t_4	t_4
3	17.0	40.0	36.6	1.7	1.1	0.5		0	t_4	t_4
4	16.0	39.0	34.6	2.2	1.6	1.1	0.5			
Example 3								1.1	t_0	t_1
0	20.0	43.0	43.0					1.1	t_0	t_1
1	23.0	46.0	44.6	0.6				0.9	t_1	t_2
2	26.0	49.0	46.2	1.2	0.7			0.7	t_2	t_3
3	29.0	52.0	47.6	1.7	1.3	0.8		0.5	t_3	t_4
4	32.0	55.0	48.9	2.2	2.0	1.5	0.9			
Example 4								1.9	t_0	t_4
0	20.0	43.0	43.0					1.9	t_0	t_4
1	30.0	53.0	51.4	0.6				0	t_4	t_4
2	30.0	53.0	49.9	1.2	0.9			0	t_4	t_4
3	30.0	53.0	48.5	1.7	1.8	0.9		0	t_4	t_4
4	30.0	53.0	47.1	2.2	2.6	1.8	0.9			
Example 5								0	t_2	t_4
0	20.0	43.0	43.0					0	t_2	t_4
1	30.0	53.0	51.4	0.6				0	t_2	t_4
2	20.0	43.0	40.5	1.2	0.9			1.1	t_2	t_4
3	30.0	53.0	48.5	1.7	1.8	0.6		0	t_4	t_4
4	25.0	48.0	42.6	2.2	2.6	1.2	0.9			

Example 3 investigates a significant increase of the total investment (10-15 % per year). This example depicts a seller's market or a region with high inflation rates. The resulting positive *ROV* recommends an advanced investment. The *ROV* is positive in all periods so that the next best period t^* is always the subsequent period.[13] The total *ROV* of the example is 1.1 M€.

Example 4 displays a more disruptive development. After the first period with a low investment, the investment suddenly steps up. This might be the case if public incentive programs are cut down. The results show that an investment in t_0 is beneficial compared to an investment in t_4, which is the next best period t^*. The real option value of an advanced investment is 1.9 M€ in this example.

Massive fluctuations of the investment are displayed in example 5. In this case, the optimal investment period is t_2. The *ROV* of the path in the current period t_0 is 0, as an advancing of the investment to t_0 is not recommended.

In order to derive a final recommendation, the expected return of the early investment has to be defined. As suggested above, a return *R* of 3 % (the value of *r*) may be used. Based on the initial investment of 20 M€, the investment threshold is thus 0.6 M€. The overall option value in this example is also 0.6 M€ (calculated as the mean of all paths (0, 0, 1.9, 1.1, 0)), therefore, a decision based on these calculations is difficult. As discussed in section 5.2.3, one option to improve the information basis for the decision is to calculate the probability of achieving savings by investing immediately. As only two out of five paths are in the money, the probability is 40 % and does hence not support an early investment.[14]

---

13 This is caused by the declining relative increase of the investment.

14 The derivation of an investment decision is hardly meaningful in this case, as the underlying stylized examples do not represent realistic and comparable scenarios with regard to expectations of future developments. Nevertheless, the results are mentioned in order to explain the calculation procedure. Chapter 6 provides more meaningful examples and the corresponding results.

5.3 Losses Perspective

The losses perspective is based on a contrary contemplation compared to the savings perspective. The delay of an investment may not only gain savings but also cause losses in case of disruptive developments that lead to rising investments. Therefore, the losses perspective aims at calculating possible losses that may occur if an investment is delayed. This calculation is less intuitive, as the real option value is, in this case, an undesirable 'value' that contains losses. Thereby, this perspective allows evaluating the monetary risk of delaying an investment.

In the following, the minimum losses calculation is described first. The results of this approach equal the maximum savings perspective in most cases. Thereafter, other contemplations that are possible within the losses perspective will be introduced and again the results of the stylized examples will be assessed.

5.3.1 Idea and Setting

As mentioned already, the losses perspective is not based on the backward induction approach as the savings perspective, but it compares the investment in t_0 with every future period t. If a delay of the investment to a future period results in an economic loss, the option is considered in the money. This contemplation is not very intuitive, as in option theory, an option that causes a loss is never in the money. With regard to the question at hand, however, this contemplation makes sense, as the option is to advance the investment compared to the latest possible period. Therefore, this contemplation can be regarded as a double negation that results again in a positive value.

Due to the missing dynamic programming approach, it is not possible to derive the optimal investment period using these calculations, as the future periods are not directly set in relation to each other. Therefore, the result is only 'delay' or 'invest immediately'. The main advantage of this perspective is the possibility to derive not only information about the best-case scenario, but also about mean or maximum losses in case of a delayed investment. These contemplations will be further discussed in 5.3.3. Beyond that and if not stated otherwise, the assumptions of the savings perspective apply accordingly.

5.3.2 Mathematical Implementation

Again, the mathematical implementation starts with the calculation of the *NPV*, which is similar to the savings perspective (cf. eq. (5-2) and (5-3)). The calculation of the option price starts in this perspective always from the starting period t_0. Apart from that, the option price *OP* is calculated similarly to eq. (5-4) in eq. (5-13) for one period and in eq. (5-14) for an arbitrary number of periods.

$$OP_{t_1} = I_{t_0} \cdot r \tag{5-13}$$

$$OP_t = \sum_{k=1}^{t} I_0 \cdot r \cdot \frac{L + 1 - k}{L} \tag{5-14}$$

The minimum losses perspective then compares the *NPV* of an investment in t_0 plus the *OP* with the *NPV* of an investment in t_1, discounted to t_0. If the delay of the investment causes a loss, the option is considered in the money. Consequently, having an option in the money has a negative economic effect for the investor. Therefore, the aim is to minimize the losses and thus the real option value. In the succeeding period t_2, the real option value is calculated based on the strategy of t_1. All paths that do not have an option in the money do not need to be regarded again (i.e. the *ROV* of the whole path is set to 0), as a delay to a later time is in any case advantageous and does not lead to a loss. Following this scheme, the *NPV* of every time t_i is compared to t_0 in order to derive the real option value *ROV* for every period until *T* with *l* indicating the losses perspective (cf. eq. (5-15)).

$$ROV_{t,mc,l} = \begin{cases} 0 & if \quad \frac{NPV_t}{(1+r)^t} < NPV_{t_0} + OP_{t_0,t} \\ \frac{NPV_t}{(1+r)^t} - (NPV_{t_0} + OP_{t_0,t}) & if \quad \frac{NPV_t}{(1+r)^t} > NPV_{t_0} + OP_{t_0,t} \end{cases} \tag{5-15}$$

All paths that are in the money for every time t until T cause a loss if the investment is not executed instantly. As all real option values in this perspective represent losses, the minimum loss per Monte-Carlo path is selected and set as option value $ROV_{mc,l}$ as displayed in equation (5-16).

$$ROV_{mc,l} = min(ROV_{t,mc,l}) \tag{5-16}$$

Finally, the mean option value of all paths, including the zero paths, is calculated in equation (5-17) and compared to the average expected return *R,* as discussed for the savings perspective (cf. eq. (5-18)). In this perspective, the real option value *ROV* represents the losses for delaying the investment, whereas *R* represents the expected return for an immediate investment. An immediate investment is recommended if the *ROV* is higher than *R.*

$$ROV_l = \frac{1}{MC} \cdot \sum_{mc=1}^{MC} ROV_{mc,l} \tag{5-17}$$

$$\begin{matrix} invest\ in\ t_0 & if & ROV_l > R_l \\ delay & if & ROV_l < R_l \end{matrix} \tag{5-18}$$

5.3.3 Further Contemplations

Apart from the minimum losses calculation (displayed as ‘standard’ in Table 5-4), the losses perspective allows further analyses with regard to possible losses that may occur when delaying (i.e. not advancing) an investment. The following alternatives may be of interest:

Table 5-4: Overview of reasonable contemplations within the losses perspective.

	Minimum	Mean	Maximum
Paths in the money	Standard	(X)	(X)
All paths (period-based)		X	X

For the paths in the money, the minimum losses calculation is recommended as described above. A calculation of the mean and maximum losses of these paths is possible by adapting eq. (5-16). The results may help to understand the order of magnitude of possible losses but the usefulness of a detailed quantitative analysis can be questioned, as there is no economic incentive to aim at mean or maximum losses.

If all paths are considered, maximum and mean contemplations are possible and more reasonable. Therefore, the analysis starts in time t_1 with the calculation of the mean or maximum (or e.g. the 0.95 or 0.98 percentile) of the option values of all paths in this period. Afterwards, t_2 and all following t_i can be analyzed accordingly. The calculation of the minimum is possible as well but is supposed to be 0 in most cases (as soon as one Monte-Carlo path is 0 in the regarded period, the minimum of this period is 0). These calculations may help the decision-maker to analyze not only the best-case but also more pessimistic developments. It needs to be emphasized, however, that the resulting values are no real option values (by definition) but represent worst-case losses for all periods. A path that is 0 in all periods except for one is still considered as a loss in this period, even though the overall option value of the paths is 0 in the standard ROA contemplation. Hence, the results are to be regarded as additional input for the decision-making that gives an idea about the amount of possible losses in a worst-case contemplation.

Again, in analogy to the savings perspective, it is possible to calculate the number of paths that are in the money and thus lead to a loss (in general or with regard to a specific period). Thereof, the probability of a loss can be derived which is also interesting for a decision-maker. For the assessments that regard all paths, the calculations of eq. (5-15) may not stop as soon as a path is out of the money but need to continue for the succeeding periods. It may be the case that in a certain setting, a delay to time t_i does not lead to a loss whereas a delay to a time later than or prior to t_i does cause a loss. These losses have to be regarded in case of maximum or average losses contemplations considering all paths.

5.3.4 Stylized Examples

The stylized examples of the losses perspective are based on the same data as those of the savings perspective; hence, the examples displayed in Table 5-2 apply accordingly. Table 5-5 displays the results of all investment examples of the losses perspective.

The first four columns equal Table 5-3 of the savings perspective. Regarding the option price *OP*, it is sufficient to calculate it from t_0 to t, due to the reverse contemplation compared to the savings perspective. The real option values *ROV* are then calculated for every period t. The last column t_{inv} has to be read from the top to the bottom. Starting in t_1, the investment is either delayed (if the option value is 0) or recommended in t_0 (if the option value is larger than 0, as it displays losses).

As for the savings perspective, example 1 supports the intuitive assumption that an advanced investment is not recommended in case of a constant investment sum. As the first comparison between period 0 and 1 already recommends a delay, the value of the example can be set to zero and further calculations (even though displayed in the table) are no longer necessary. In contrast to the savings perspective, this perspective cannot display the optimal investment time, as the periods are not set in relation to each other, but are only compared to the current period t_0. Therefore, t_{inv} can only be either t_0 or ‘delay’.

Table 5-5: Minimum losses results of the stylized investment examples [M€].

t	I	NPV_t	NPV_{t_0}	OP_t	ROV	t_{inv}
Example 1					0	delay
0	20.0	43.0	43.0			
1	20.0	43.0	41.7	0.6	0	delay
2	20.0	43.0	40.5	1.2	0	delay
3	20.0	43.0	39.3	1.7	0	delay
4	20.0	43.0	38.2	2.2	0	delay
Example 2					0	delay
0	20.0	43.0	43.0			
1	19.0	42.0	40.8	0.6	0	delay
2	18.0	41.0	38.6	1.2	0	delay
3	17.0	40.0	36.6	1.7	0	delay
4	16.0	39.0	34.6	2.2	0	delay
Example 3					1.1	t_0
0	20.0	43.0	43.0			
1	23.0	46.0	44.6	0.6	1.1	t_0
2	26.0	49.0	46.2	1.2	2.0	t_0
3	29.0	52.0	47.6	1.7	2.9	t_0
4	32.0	55.0	48.9	2.2	3.6	t_0
Example 4					1.9	t_0
0	20.0	43.0	43.0			
1	30.0	53.0	51.4	0.6	9.4	t_0
2	30.0	53.0	49.9	1.2	5.8	t_0
3	30.0	53.0	48.5	1.7	3.8	t_0
4	30.0	53.0	47.1	2.2	1.9	t_0
Example 5					0	delay
0	20.0	43.0	43.0			
1	30.0	53.0	51.4	0.6	7.9	t_0
2	20.0	43.0	40.5	1.2	0	delay
3	30.0	53.0	48.5	1.7	3.8	t_0
4	25.0	48.0	42.6	2.2	0	delay

The examples 2 and 3 also confirm the results of the maximum savings perspective. Example 3 has a positive real option value, which recommends an immediate investment. As explained above, the aim is to minimize the losses. Therefore, the *ROV* of example 3 is 1.1 M€, which is the minimum of all real option values in this example. Accordingly, example 4 follows the result of the maximum savings perspective. Due to the increasing investment in t_1, it also recommends an immediate investment. Example 5 displays the difficulty of the methodology to identify the optimal investment period. As both periods 2 and 4 recommend a delay, it is not possible to display the optimal period. Therefore, the result of example 5 is simply 'delay'.

In total, the results of the minimum losses perspective equal those of the savings perspective for these few paths. As mentioned already, the results may deviate for certain paths, an example will be provided in the next section.

Figure 5-2 displays the NPV_t of the project for an investment in t for all examples. The solid line represents the investment threshold (*IT*) based on the *NPV* of the current time t_0. It is calculated according to equation (5-19) as the sum of the compounded investment in t_0 and the option price for the corresponding number of waiting periods.

$$IT_t = NPV_{t_0} \cdot (1 + r)^t + OP_t \quad (5\text{-}19)$$

Below this line is the 'waiting region', above the line the 'execution region'. Hence, if the *NPV* of all time steps in one scenario are above the line, the investor should invest immediately. If one or more *NPV* are below the threshold, the investor is supposed to wait.

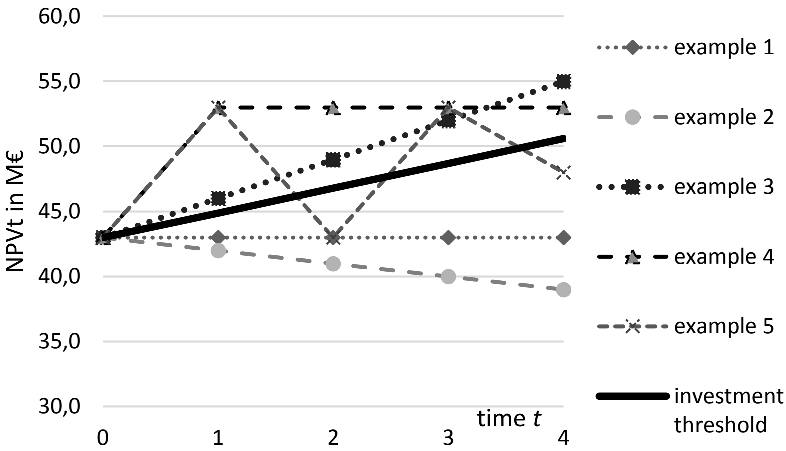

Figure 5-2: NPV of the five project scenarios in relation to the investment threshold (all expenses discounted to t).

In contrast to typical optimal stopping problems, the investment threshold displayed in Figure 5-2 is not valid throughout the considered decision-making interval, but needs to be updated, as soon as new information is available (typically in the next period). This is caused by the obligation to invest at the end of the decision-making period, such that the investor always needs to compare the current state with expected future states and not with a fixed profitability threshold that might never be met. Therefore, this approach is a typical rolling horizon application that needs to be updated and reconsidered regularly.

5.4 Consolidation and Comparison of Both Perspectives

To derive a decision, the decision-maker can but does not have to consider both perspectives. The savings perspective is more intuitive and may thus be more transparent and comprehensible. It further allows the calculation of the optimal investment time based on current information. If the investment is not executed immediately, the determination of the optimal investment time for the paths out of the money may be interesting with regard to future planning. If a considerable number of paths recommend an investment in the near future, prices and other influencing factors can be monitored closely with regard to the investment decision. The intervals between the considered time steps may be shortened in order to achieve a higher granularity. If most paths recommend an investment towards the end of the decision-making period, the investment decision and the influencing parameters should still be monitored regularly, but the effort in the near future may be reduced.

Particularly in the case of tight decisions or risk-averse decision-makers, the losses perspective may add additional value, as worst-case scenarios can be taken into account as well. Furthermore, the number of paths in the money can be calculated for both perspectives. The integration of such parameters emphasizes the strong influence of the risk perception of the decision-making board. In any case, the additional information about possible future outcomes adds value, particularly if project or company-specific information (e.g. liquidity projections) are set in relation to the results.

The real option values of both perspectives are mostly similar. Differences may occur due to the different base values of the option price (*OP*). In the savings perspective, the option price is based on the simulated investments of the periods in the future, whereas in the losses perspective, it is always based on the initial investment in t_0. Differences between the real option values may occur if the real option values of future periods in the savings perspective lead to different next best periods t^*. An exemplary path with differing results is displayed in Table 5-6. A quantitative analysis of the deviations for a Monte-Carlo simulated case study will be provided in section 6.4.1.1.

Table 5-6: Exemplary investment path with differing option values in the savings and the losses perspective in M€.

t	I	NPV_t	NPV_{t_0}	OP				ROV	t_{inv}	t*
				t_0	t_1	t_2	t_3			
Savings perspective								0.13	t_0	t_2
0	20.0	43.0	43.0					0.13	t_0	t_2
1	22.0	45.0	43.7	0.6				0	t_2	t_2
2	24.0	47.0	44.3	1.2	0.7			0.14	t_2	t_4
3	26.5	49.5	45.3	1.7	1.3	0.7		0	t_4	t_4
4	28.5	51.5	45.7	2.2	1.9	1.4	0.8			
Losses perspective								0.09	t_0	
0	20.0	43.0	43.0					0.09	t_0	
1	22.0	45.0	43.7	0.6				0.13	t_0	
2	24.0	47.0	44.3	1.2				0.59	t_0	
3	26.5	49.5	45.3	1.7				0.54	t_0	
4	28.5	51.5	45.7	2.2						

The exemplary path in Table 5-6 shows the reason for the deviation, which is the reference value of the option price. While the option price of the minimum losses perspective always refers to an investment in t_0, it is adapted to the development of the investment in the savings perspective. This leads (for the example at hand) to a shift of the next best period *t** in the savings perspective, as the *ROV* in period 1 and 3 are slightly below 0 and, hence, are set to 0. Therefore, the total *ROV* differs between the two perspectives. Such deviations may occur if the investment fluctuates closely around the investment threshold. The absolute deviation can hence be considered moderate and the example in chapter 6 will show that the impact caused by this effect is usually comparably low.

6 Application and Results

The most important prerequisites for real options to have value are high uncertainty and high flexibility (Brach 2003). These two features represent the central idea of real options: using operational and managerial flexibility to respond to future uncertainty. Therefore, real options provide value, if the project, in this case the mandatory investment in an emission abatement installation, incorporates them.

The extent to which projects in the context of emission abatement in LCP meet these features may differ severely, depending on local circumstances. In order to assess typical situations, the chapter at hand presents exemplary applications of the models described above. Two plants will be investigated, one in the techno-economic-political context of the EU and one in the context of India. Several scenarios will be introduced and assessed in order to evaluate the impact of policy measures and economic fluctuations in this context.

The chapter is structured in six sub-chapters, starting with the description of the two case study plants and the derivation of data-sets, followed by the calculation results of the techno-economic model and the ROA and completed with a section on decision-making and one on policy implications from a more general and comprehensive perspective.

6.1 Case Study Descriptions

Table 6-1 displays an overview of the considered case study and scenario choices, without going into detail regarding the underlying data. For every example, one alternative of each of the first three lines has to be selected. These alternatives are logically exclusive alternatives, which cannot be combined or left aside. A reasonable case study always requires the consideration of one plant with one abatement technique and either the base or tight ELV (the different ELV are applicable for EU SCR only).

In contrast, the political and economic choices below the bold line can be selected and combined according to the needs or expectations of the decision-maker, considering that a ROA only delivers reasonable results, if at least one uncertain, i.e. stochastically simulated, parameter is considered. All different combinations can theoretically be regarded in order to understand the behavior of the methodology and to derive conclusions, even though some combinations are more relevant in practice than others are.[1]

Table 6-1: Overview of case study/scenario combinations.

<table>
<tr><td>Plant choices</td><td colspan="3">EU plant</td><td colspan="3">Indian plant</td></tr>
<tr><td>Abatement technique choices</td><td colspan="3">SNCR</td><td colspan="3">SCR</td></tr>
<tr><td rowspan="2">Political choices</td><td colspan="3">Base ELV</td><td colspan="3">Tight ELV</td></tr>
<tr><td colspan="2">Discontinued subsidies</td><td colspan="2">Emission fees</td><td colspan="2">NO_X market</td></tr>
<tr><td>Economic choices</td><td colspan="3">Increasing investment</td><td colspan="3">High consumable costs</td></tr>
</table>

In the following, the combination of plant location and abatement technique is denoted as case study, whereas all combinations of political and economic choices under investigation (no matter if deterministic or stochastically simulated) are named scenarios. The stochastically simulated choices are

[1] E.g. the combination of emission fees and a NO_X market seems very unlikely, as both political instruments would target the same parameter, in this case the total NO_X emissions.

displayed in italic type in the table. An introductory description of the considered choices and underlying assumptions will be provided in the following, before the detailed datasets will be introduced in section 6.2.

6.1.1 Technical Assumptions and Data

The calculations in the following are based on the fixed lifetime contemplation (cf. 5.1.3). It is considered reasonable to select one alternative for the calculations at hand in order to ensure comparability. From a technical point of view, it would also be possible to select the fixed end of life contemplation. As mentioned already, this selection has to be based on the circumstances of a considered plant in a practical application.

The case studies only regard SCR and SNCR investments, as they are considered most interesting with regard to a real option application. Due to the large share of investment expenditures (compared to operating expenses) and the generally lower total expenditures for primary measures, the overall impact of fluctuations (in absolute numbers) is a lot lower and the impact of managerial flexibility is hence considered lower for primary measures (cf. also Wiatros-Motyka and Nalbandian-Sugden 2018). Nevertheless, the investigation of primary emission abatement investments according to the methodology described above is possible, if the user possesses sufficient data.

The technical feasibility of the selected techniques has to be investigated separately, as the plant-specific conditions may require particular consideration. Such peculiarities have to be assessed on-site by technical experts. Therefore, the results presented below are subject to technical feasibility. The values assumed for the technical parameters will be introduced in detail in 6.2. The values for the European Plant are based on the results of a TFTEI survey, complemented by reference values from literature. The values for the Indian plant were adapted from the EU plant to the local circumstances based on the insights of the recent report from Wiatros-Motyka and Nalbandian-Sugden (2018).

6.1.2 Political and Economic Assumptions and Data

The political and economic scenarios aim at displaying the field of action for policy and investors. Therefore, the underlying data aims at being realistic in the way that the scenarios under investigation could principally happen in the future. The aim is not to identify the most likely scenario for the future (based on current projections) but to assess possible outcomes of different settings. Therefore, less likely scenarios are selected as well and variables are altered broadly in order to demonstrate their impact on the resulting decisions.

With regard to the ELV for the EU, a base case is selected, which uses the ELV that is currently in force.[2] A second scenario investigates a lower ELV ('tight ELV') that might be implemented in the future. The detailed values for all parameters are listed in section 6.2.

The operating costs are summarized in all scenarios, as a fluctuation of only one operating cost component within a reasonable scale is not expected to affect the decision considerably. In order to account for the long lifetime of the considered type of investments, an inflation rate is assumed for all future costs such as operating costs and NO_X fees. The comparison of the project values with regard to a delay of the investment is based on the equations introduced in chapter 5.

2 As the BAT-AEL are currently the most stringent regulation in force in the EU, there is not one limit, but an upper and lower limit, as the BAT-AEL are provided as a range. It will be a task for the national governments to select and implement an ELV within this range.

6.2 Input Data

The following section provides an overview of the plant data for the case studies described above. All technical and economic parameters for the calculations and their references are provided for the European SCR. The EU SNCR and the Indian examples are based on the same data unless stated otherwise.

6.2.1 European Plant

The data for the European plant is predominantly based on a dataset that was sent to TFTEI during a survey in 2013 for a high-dust SCR installation. The data is hence comparably recent and the parameters can be assumed realistic, even though this does not mean that they can be taken as reference values for all sorts of plants due to the technical uniqueness of the installations. The missing data is completed by reference values from literature and supplier publications. The only value that was not taken over directly from the TFTEI questionnaire is the specific catalyst volume. This will be discussed in more detail in the EU-SCR section. For the ELV, a base value of 200 mg/Nm³ of NO_X in the flue gas at reference O_2-concentration is used.[3] As target values, three different values will be investigated. The applicable ELV according to the upper end of the BAT-AEL range given in the revised BREF LCP is 150 mg/Nm³. Therefore, the implementation of an SNCR installation is investigated that aims at a new stack emission level of 150 mg/Nm³. Furthermore, a reduction to 80 mg/Nm³, which accounts for the lower end of the range of the BAT-AEL (85 mg/Nm³), will be investigated as well as an even more stringent level of 40 mg/Nm³. For the latter two, the installation of an SCR system is assumed.

[3] With the IED, an emission level of 150 mg/m³ was already implemented for many plants. This base value, however, would be difficult to assess in the given context, as it already requires 2° measures in most plants. Hence, an upgrade of 2° measures would be necessary instead of a new installation, which cannot directly be assessed by the techno-economic model.

A further assumption for both plants and techniques is that the reagent is bought at injection concentration so that no further dilution on-site is necessary. The cost of additional water for dilution is hence zero. The excess air factor is set to 1.2. Even though Meinke (2014) assumes this value to increase in case of e.g. part load operation, it is considered constant in this work, as there is no detailed information available and the resulting error is considered acceptable with regard to study level accuracy.[4] The cost caused by the pressure drop is calculated based on the factor of 0.007 Wh/(mbar·Nm³) used in the online calculation tool of CAGI (2018).

6.2.1.1 SCR

Table 6-2 displays the values and references to be considered for the SCR in the European plant. The data listed in this table does not vary among the different scenarios to be investigated.

The missing parameters that are altered in the different scenarios are provided in Table 6-3 for the EU SCR base ELV scenario with their corresponding references. The catalyst volume is calculated according to the US EPA methodology, even though a specific catalyst volume was provided in the questionnaire. This value, however, cannot be adapted to the required abatement efficiency, as there is no information available in the questionnaire concerning the initial abatement efficiency. Therefore, the parameters of the questionnaire together with the assumptions for the ELV to be achieved have been used to calculate the catalyst volume. The results are in the same range as the provided value and can hence be assumed reasonable.[5]

4 Particularly as part-load and startup/shutdown operation is not considered in the case studies at hand.

5 A precise comparison of the US EPA value with the value in the questionnaire is not possible, as the NO_X inlet concentration is not provided in the questionnaire. Further assumptions that have been made for the US EPA calculation: inlet temperature: 340°C (based on the value for high-dust installations provided by Moulton 2015); ammonia slip: 5 ppm.

Table 6-2: Input parameters of the European plant SCR case study.

Parameter	Value	Unit	Reference
Technical parameters			
Thermal capacity	1 500	MW_{th}	TFTEI data
Gross electric efficiency	40	%	TFTEI data
Operating hours	5 500	h/a	TFTEI data
Reference O_2-content	6	%	LCP BREF
Excess air ratio	1.2	-	Meinke (2014)
Carbon in ash	5	%	TFTEI (2015a)
Fuel parameters			
LHV	28.71	MJ/kg	TFTEI data
Sulfur mass fraction	0.62	wt.-%	TFTEI data
Ash mass fraction	12.5	wt.-%	TFTEI data
Moisture mass fraction	9.00	wt.-%	TFTEI data
NO_X abatement parameters			
Emissions before abatement	200	mg/Nm³ ref-O_2	assumption
N° of catalyst regenerations	1	-	TFTEI data
Catalyst lifetime	36 000	h	TFTEI data
Stoichiometric ratio	0.8	-	TFTEI data
Type of reagent	ammonia	-	TFTEI data
Reagent concentration[6]	24.9	%	TFTEI data
Pressure drop	13	mbar	TFTEI data
Power demand of pressure drop	0.007	Wh/mbar·Nm³	CAGI (2018)
Direct electricity consumption	37.5	kW	TFTEI data
Economic parameters			
Lifetime	20	a	assumption
Interest rate	3	%	cf. 5.1.5
Fixed O&M costs	2	% TCI	assumption
Catalyst regeneration price	0.5·cat. price	€/m³	TFTEI data

6 The concentration of 24.9 % was mentioned in the TFTEI questionnaire. The value is somehow surprising, as e.g. US EPA (2016) mentions a commonly used concentration of 29.4 %. Thus, this value might be a typo. However, it is technically possible to use a reagent with this concentration. Therefore, it is used for the further calculations.

Table 6-3: Base values for EU SCR scenario calculations.

Parameter	Base value	Unit	Reference
Specific investment	33.3	€/kW_{th}	TFTEI data
ELV (approximately)	85	mg/Nm³ ref-O_2	LCP BREF
Emissions after abatement	80	mg/Nm³	BAT-AEL
Catalyst volume	391	m³	US EPA (2016)
Reagent price	300	€/t	assumption
Catalyst price	5 000	€/m³	TFTEI data
Electricity price	32.89	€/MWh	Fraunhofer ISE (2018)
NO_X price	0	€/t	assumption

The assumption for the reagent price is based on the data provided by Himes (2004), Schnitkey (2016), Tsitsiriki et al. (2007) and US EPA (2016). As the prices in these references differ rather significantly, an assumption has to be made that may differ for other regions and deviates based on the development of the ammonia price on international markets.

The electricity price is based on the annual average day ahead auction price in Germany in 2017 (Fraunhofer ISE 2018). This price is considered, as the value of the electricity used by the plant itself is assumed to equal the lost revenue that could be achieved when selling the electricity externally. In a European comparison, this value is comparably high so that it may be adapted for plants in other regions even within Europe. The order of magnitude of the total electricity consumption (direct consumption plus pressure drop) has also been benchmarked with the study of Yang et al. (2018), which confirms the reasonability of the values.

The catalyst lifetime provided in the questionnaire appears comparably high. However, the number of catalyst regenerations (one) is comparably low. Hence, the resulting overall costs can be expected to be within a realistic range. The variation of the values in Table 6-3 for the scenarios to be investigated will be introduced in more detail in sections 6.2.3 and 6.4.

6.2.1.2 SNCR

Both the fixed input values and the base values of the scenarios for the SNCR example are listed in Table 6-4. Only the values that differ from the SCR Europe example are mentioned here. In general, the SNCR calculation requires less data than the SCR due to the missing catalyst.

For the specific investment, two references are mentioned, as the data in the TFTEI study was scarce for the specific investment of SNCR installations. Yet, the TFTEI average value of 15 €/kW_{th} is confirmed by Reis (2010) so that it can be considered realistic. The other technical parameters stem from another TFTEI questionnaire.

Table 6-4: Input parameters of the European plant SNCR case study. Only the parameters that differ from the SCR case are listed. For all other parameters refer to Table 6-2 and Table 6-3.

Parameter	Value	Unit	Reference
Technical parameters	unchanged		
Fuel parameters	unchanged		
NO_X abatement parameters			
ELV (approx.)	150	mg/Nm³ ref-O_2	LCP BREF
Stoichiometric ratio	3	-	TFTEI data
Pressure drop	1.5	mbar	TFTEI data
Direct electricity consumption	11	kW	TFTEI data
Economic parameters	unchanged		
Base values for scenarios			
Specific investment	15	€/kW_{th}	TFTEI data, Reis (2010)
Emissions after abatement	150	mg/Nm³	BAT-AEL

6.2.2 Indian Plant

For a plant in India, the operating circumstances differ from a European plant. Nevertheless, the report of Wiatros-Motyka and Nalbandian-Sugden (2018) confirms the possibility of using SCR and SNCR system in Indian plants. Even though the design of the systems has to be adapted to the specific local circumstances, the study level cost calculation can be assumed applicable for India as well, if specific parameters and prices are adapted accordingly. The input data that defers from the EU example is listed in Table 6-5. All missing values are equal to the EU example. For India, two technological alternatives shall be investigated, SCR and SNCR.

The ELV for NO_X that came into force in 2017 is 300 mg/m³ for all units that were installed between 2004 and 2016 and 100 mg/Nm³ for all units installed from 2017 onwards (Wiatros-Motyka and Nalbandian-Sugden 2018). Therefore, two examples shall be investigated, an SNCR installation for achieving an ELV of 300 mg/Nm³ and an SCR installation for 100 mg/Nm³. The considered plant is equal to the European plant with regard to its capacity and efficiency.[7] Its emissions before installing a secondary abatement system are assumed to be 600 mg/Nm³, which is realistic if primary measures are already implemented. For transparency reasons, the prices are also displayed in Euro, even though this is not the local currency.

The first important adaptation for an Indian plant refers to the coal. Most Indian coals have very high ash contents but low moisture contents (Wiatros-Motyka and Nalbandian-Sugden 2018). This causes some difficulties, particularly in high dust installations, nevertheless modern installations are able to cope with this situation. In order to account for the difficulties caused by the high ash content, the lifetime of the catalyst is reduced to the lower end of

[7] This might not be perfectly realistic, yet it facilitates comparisons among the examples and at least the technical performance standards of modern plants are mostly comparable to EU standards (Wiatros-Motyka and Nalbandian-Sugden 2018).

the range that has been identified in the TFTEI (2015a) study. The catalyst volume is again calculated according to the US EPA (2016) methodology and the pressure drop is adapted in order to account for the higher catalyst volume.

Table 6-5: Input parameters of the Indian plant SCR and SNCR case studies.

Parameter	Value	Unit	Reference
Technical parameters	unchanged		
Fuel parameters			
LHV	18.35	MJ/kg	Wiatros-Motyka and Nalbandian-Sugden (2018)
Sulfur mass fraction	0.61	wt.-%	
Ash mass fraction	37.13	wt.-%	
Moisture mass fraction	3.6	wt.-%	
NO_X abatement parameters			
ELV (SCR)	100	mg/Nm³ ref-O_2	Wiatros-Motyka and Nalbandian-Sugden (2018)
ELV (SNCR)	300	mg/Nm³ ref-O_2	
Emissions before abatement	600	mg/Nm³	assumption
Catalyst lifetime (SCR)	24 000	h	Adapted from EU plant
Pressure drop (SCR)	14	mbar	Adapted from EU plant
Economic parameters	unchanged		
Values for deterministic scenarios			
Specific investment (SCR)	31.4	€/kW_{th}	Adapted from EU plant
Specific investment (SNCR)	15	€/kW_{th}	Adapted from EU plant
Emissions after abatement (SCR)	100	mg/Nm³	ELV
Emissions after abatement (SNCR)	300	mg/Nm³	ELV
Catalyst volume (SCR)	543	m³	US EPA (2016)
Reagent price	375	€/t	Adapted from EU plant
Catalyst price (SCR)	5 000	€/m³	TFTEI data
Electricity price	28	€/MWh	assumption
NO_X price	0	€/t	assumption

The specific investment value for SCR has been adapted to the size of the installation (based on the size of the catalyst) using an economies of scale exponent of 0.7. The resulting value has been multiplied with 0.75, as the study of Krishnan (2016) assumes lower costs for clean air installations in India, due to the competitive market situation. He even suggests a factor of 0.5 for Indian installations compared to EU installations, yet this assumption is considered rather short-term oriented and may level off over time. Therefore, in order to avoid an underestimation of costs, a factor of 0.75 is assumed.

For SNCR, the specific investment value remains the same, compared to the EU-SNCR case study. This can be explained by two influences that are expected to compensate each other. The first one are the lower prices for installations in India and the second one is the larger size of the installation with a significantly higher amount of reagent to be injected into the boiler. Yet, the size dependency of SNCR installations is comparably low, so that a calculation as for SCR can be expected to deliver wrong results.[8]

The reagent price of the EU example is multiplied with a factor of 1.25, as CSE (2016) states that currently, all reagents have to be imported by Indian plants. Therefore, the costs are expected to be higher than they are at locations closer to the production sites.

The derivation of a suitable electricity price is very difficult for India, as information about the sales prices of power plants is not publicly accessible in English language (to the best of the author's knowledge). The only available prices are the consumer prices. For industrial consumers, the Indo-German AHK (2018) lists a price of 56 €/MWh. It is assumed that the sales price of a power plant is significantly lower. Therefore, half of this price is assumed as

[8] The economies of scale calculation described for the SCR system would lead to a higher specific investment for SNCR than for SCR if the reagent consumption is used as capacity reference. This cannot be considered a realistic result.

input value for the calculations in the following. This, however, is a rather arbitrary assumption that needs to be checked for plausibility in a real-world application.

6.2.3 Scenario Description

Table 6-6 displays an overview of the influence of the scenarios on the cost parameters. The parameters marked with X have to be adapted in the corresponding scenario. All scenarios are based on the full load approach, i.e. part load operation is not considered, as there is no sufficient database available for a realistic part load study.

Table 6-6: Scenario-influenced cost parameters.

Parameter	Tight ELV	Subsidies	Emission fees	NO_X market	Increasing investment	High consumable costs
Total investment	X	X			X	
NO_X emission cost			X	X		
Reagent cost	X					X
Catalyst cost	X					X
Electricity cost	X					X
Fixed operating costs	X					

For the tight ELV scenario, which is defined as a deterministic[9] scenario and only considered in the EU-SCR example, it is assumed that an ELV of 40 mg/Nm³ needs to be met. Therefore, the catalyst volume is recalculated using the equation of US EPA (2016). According to the Indian SCR example, it

[9] I.e. it does not consider uncertainty with regard to its future development.

is assumed that the specific investment increases by the same factor as the catalyst volume, reduced by an economies of scale exponent of 0.7. In the given case, the catalyst volume increases by approximately 20 %, while the total investment increases by about 14 %. The reagent consumption is recalculated according to the techno-economic model, as it increases due to the higher amount of NO_X to be reduced. The electricity cost increases as well, as the pressure drop is assumed to rise by 2.5 mbar caused by an additional catalyst layer.

The subsidies scenario influences only the total investment, yet it is modeled as one of the scenarios concerning uncertainty, i.e. a stochastic process is assumed to simulate its future development. The precise values of the subsidy and the parameters of the underlying jump process will be introduced in detail in section 6.4.

Both the scenarios for emission fees and NO_X markets influence only the emission costs, which are 0 in the standard case. Hence, both scenarios consider an additional cost that is created directly by policy intervention. The emission fees scenario assumes a predefined price for the future and is hence deterministic, whereas the NO_X market scenario assumes an uncertain stochastic development of the prices in the future.

As there are only few fee- or tax-schemes and NO_X markets installed worldwide, these scenarios aim at identifying approximate threshold values for achieving a significant influence on the decision in the given settings. With regard to the implementation, NO_X fees could be considered as negative opportunity costs, i.e. as opportunity benefits, because the fees to be paid after the investment are lower than before (caused by the lower total NO_X emissions after installation). Due to the NPV based calculation, however, the NO_X fees before and after installation are directly considered so that a consideration of opportunity benefits is not necessary.

The increasing investment scenario is again a stochastically simulated scenario that assumes an increasing investment following a Geometric Brownian Motion. The drift and volatility parameters to be investigated will be introduced in section 6.4.

Finally, the high consumables scenario assumes a massive increase in the prices of all consumables by 100 %, while the investment and fixed operating costs are expected to remain constant. In order to limit the number of scenarios to a reasonable amount, this is also considered a deterministic scenario. Variations of sub-items of the operating costs (e.g. only electricity costs) or minor increases of prices can be expected to have a comparably low influence with regard to the overall decision and are hence not assessed in more detail in the case studies at hand.

Combinations of the scenarios described above are also possible. Apart from the combination of the emission fees scenario with a NO_X market scenario, all combinations (also combinations of two or more basic scenarios) seem generally considerable. In the following, all basic scenarios in combination with the different case studies will be assessed as well as a selection of scenario combinations that appears particularly interesting. An assessment of all possible combinations would go beyond the scope of this work, as 110 different combinations of scenarios are theoretically possible in the considered framework, not including the number of different parameter values, which is theoretically unlimited.

For the simulation of the stochastic investment processes, one set of random numbers has been created that is reused for all calculations. Therefore, deviations with regard to the results are not created by deviations of the sets of random numbers. Both the increasing investment scenario and the NO_X market scenario are modeled as a Geometric Brownian Motion (GBM), while the discontinued subsidy scenario is modeled as a Markov jump process that interferes with the GBM of the investment development in the random walk approach. Therefore, increasing investments and discontinued subsidies can be investigated and altered at the same time. Both stochastic processes have been introduced in section 3.5.4.

6.3 Results of the Techno-economic Model

This section displays the results of the techno-economic model. It does not consider uncertainty, hence, only the deterministic scenarios are assessed with this part of the model, whereas the stochastically simulated scenarios follow as results of the ROA model in section 6.4.

6.3.1 European Plant

In the following, the results of the EU plant with the two SCR and the SNCR case studies will be displayed. The base case is displayed as well as the deterministic scenarios 'high consumable costs' and 'emission fees'.

6.3.1.1 SCR

Table 6-7 displays the calculation results for all deterministic scenarios of the SCR case study. The different ELV are denoted as 'base' (80 mg/Nm³) and 'tight' (40 mg/Nm³). The 'standard' scenario uses the data presented in Table 6-3, whereas '↑ consumables' represents the high consumable cost scenario that assumes double prices for the three consumables. The 'emission fees' scenario equals the standard scenario except for the consideration of emission fees before and after the implementation of the abatement measure.

Table 6-7: Results of the techno-economic model for all deterministic EU-SCR scenarios. (Total operating costs do not consider emission fees and refer to the base year t_0. A NO_X fee of 2 000 € per ton of NO_X emitted is assumed and the NO_X cost is also displayed for the base year t_0. The cost in future periods will increase according to the considered inflation rate).

Parameter	Unit	Base	Tight				
Catalyst volume	m³	391	480				
Reagent consum.	t/a	1 501	2 001				
Energy consum.	MWh/a	11 753	16 620				
NO_X before inv.	t/a	2 107	2 107				
NO_X after inv.	t/a	843	422				
Total investment	k€	49 950	57 600				
		Standard		↑ Consumables		Emission fees	
		Base	Tight	Base	Tight	Base	Tight
Catalyst cost	k€/a	224	275	448	550	224	275
Reagent cost	k€/a	450	600	901	1 201	450	600
Electricity cost	k€/a	387	547	773	1 093	387	547
Fix O&M cost	k€/a	999	1 152	999	1 152	999	1 152
NOx cost before	k€/a	-	-	-	-	4 214	4 214
NOx cost after	k€/a	-	-	-	-	1 686	844
Total operat. cost	k€/a	2 060	2 574	3 121	3 996	2 060	2 574

6.3.1.2 SNCR

The investments and annual costs of the SNCR case study displayed in Table 6-8 are considerably lower than those of the SCR example. One parameter that exceeds the corresponding SCR parameter is the reagent cost, which is caused by the significantly higher stoichiometric ratio in SNCR applications. In total, both the investment and operating costs are about half the amount for SNCR compared to SCR.

The total emission fees to be paid by the plant operator are considerably higher for SNCR installations, as the total amount of NO_X emitted is the same in the initial state and higher than in the SCR example after the installation of the abatement system. Therefore, the influence of emission fees on the final decision can be expected to be higher for SNCR installations. This aspect will be assessed in more detail in section 6.4.

Table 6-8: Calculation results of the techno-economic model for all deterministic EU-SNCR scenarios. (The comments of Table 6-7 apply accordingly).

Parameter	Unit	Value		
Reagent consumption	t/a	2 345		
Energy consumption	MWh/a	214		
NO_X before investment	t/a	2 107		
NO_X after investment	t/a	1 580		
Total investment	k€	22 500		
		Base	↑ Consumables	Emission fees
Reagent cost	k€/a	704	1 407	704
Electricity cost	k€/a	7	14	7
Fix O&M cost	k€/a	450	450	450
NOx cost before	k€/a	-	-	4 214
NOx cost after	k€/a	-	-	3 160
Total operating cost	k€/a	1 161	1 871	1 161

6.3.2 Indian Plant

The main difference between the European and the Indian plant with regard to the costs of the NO_X abatement installation is the amount of NO_X to be reduced. With an initial emission of 600 mg/Nm³, the plant emits three times the amount of NO_X compared to the European plant. Therefore, particularly the operating costs are significantly higher. The detailed numbers will be provided in the following.

6.3.2.1 SCR

Table 6-9 displays the calculation results for the Indian SCR plant in the same structure as above. As mentioned already, the costs are displayed in Euro in order to allow for comparison with the EU plant results. Due to the higher amount of NO_X to be abated in the Indian plant, the catalyst is larger and the consumable demand is generally higher. Because of the reduced specific investment, however, the total investment is comparable to the EU installation. Therefore, the share of operating costs compared to the initial investment is higher. The effects thereof with regard to the decision-making will be investigated in more detail in section 6.4.

Table 6-9: Calculation results of the techno-economic model for all deterministic Indian plant SCR scenarios. (The comments of Table 6-7 apply accordingly except for an initial NO_X fee of 500 € per ton assumed here).

Parameter	Unit	Value		
Catalyst volume	m³	543		
Reagent consumption	t/a	6 472		
Energy consumption	MWh/a	13 336		
NO_X before investment	t/a	6 540		
NO_X after investment	t/a	1 090		
Total investment	k€	47 100		
		Base	↑ Consumables	Emission fees
Catalyst cost	k€/a	466	933	467
Reagent cost	k€/a	2 427	4 854	2 427
Electricity cost	k€/a	373	747	373
Fix O&M cost	k€/a	942	942	942
NOx cost before	k€/a	-	-	3 270
NOx cost after	k€/a	-	-	545
Total operating cost	k€/a	4 209	7 476	4 209

The influence of NO_X fees on the NPV of the total project increases as well, as the amount of NO_X emitted before and after the investment is higher. Therefore, and due to the economic situation in India compared to the EU, a lower base value of 500 Euro per ton is assumed for the emission fees scenario. This value still leads to considerable NO_X costs, in particular before the installation of the SCR.

6.3.2.2 SNCR

For the results of the Indian SNCR application, the statements for SCR apply accordingly and to an even larger extent. While the consumable costs in the base scenario of the Indian SCR are about 3.1 times those of the European plant SCR, the consumable costs of the Indian SNCR are even 7.7 times those of the European SNCR. This is primarily caused by the consumption of reagent, which increases massively due to the high stoichiometric ratio and the larger total amount of NO_X to be abated.

Table 6-10: Calculation results of the techno-economic model for all deterministic Indian plant SNCR scenarios. (The comments of Table 6-9 apply accordingly).

Parameter	Unit	Value		
Reagent consumption	t/a	14 561		
Energy consumption	MWh/a	223		
NO_X before investment	t/a	6 540		
NO_X after investment	t/a	3 270		
Total investment	k€	22 500		
		Base	↑ Consumables	Emission fees
Reagent cost	k€/a	5 460	10 921	5 460
Electricity cost	k€/a	6	12	6
Fix O&M cost	k€/a	450	450	450
NOx cost before	k€/a	-	-	3 270
NOx cost after	k€/a	-	-	1 635
Total operating cost	k€/a	5 917	11 383	5 917

6.4 Results of the ROA model

The results in the following are calculated by the ROA model described in chapter 5, based on the results of the techno-economic model in section 6.3. The NPV calculation is based on a matrix that assigns every cash flow to the period of occurrence so that all cash flows are discounted correctly. All future costs (i.e. operating costs and NO_X fees, if applicable) are considered to increase based on an inflation rate of 1.5 %. The investment in future periods is stochastically modeled according to the scenario under investigation. The discount rate is assumed to be 3 % and all calculations are based on the fixed lifetime contemplation with 100 000 Monte-Carlo simulated paths.

A full list of results for all case study installations and investigated scenarios is provided in Annex B. Selected results will be introduced and discussed in the following. The return R is considered in order to enable a comparison of the absolute ROV of different case studies. In this work, R is calculated as the ROV divided by the investment at time t_0 as discussed in 5.1.1.6.

6.4.1 European Plant SCR

The results of the deterministic scenarios for the SCR installation in the European plant have been displayed already. These values are now used as base values for the further calculations. Thus, the calculated values are the cash flows at time t_0 that are then either stochastically simulated or extrapolated based on the inflation rate in order to derive the cash flows of future periods.

The following sections display exemplary results for the increasing investment, the NO_X market, and the discontinued subsidies scenario. As mentioned already, it is not possible to display a full range of results, as unlimited combinations of calculation parameters are possible. Therefore, interesting examples within a reasonable range are investigated and displayed.

6.4.1.1 Increasing investment

Bevor investigating the results of the increasing investment scenario, Figure 6-1 displays exemplary Monte-Carlo simulated paths for the increasing investment base ELV scenario.

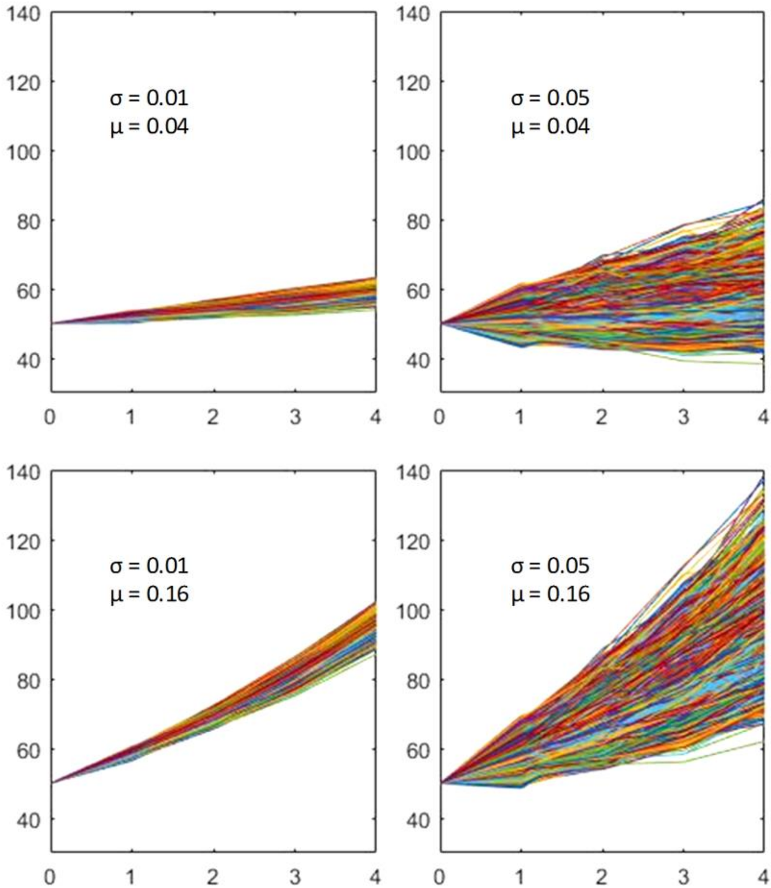

Figure 6-1: Development over time of the first 10 000 Monte-Carlo simulated investment paths for the increasing investment scenario, base ELV [x-axis: time; y-axis: investment in M€].

The paths in the figure represent the investment at every considered time *t*. The investment is not discounted and other cash flows (e.g. operating costs) are not considered, as only the investment and not the total NPV is considered. The selected examples represent the lowest and the highest drift rates for the increasing investment example in order to show the range of possible developments. While the low drift rate of 0.04 leads to a rather gentle increase, the high drift rate of 0.16 causes more than a doubling of the investment over the five periods. Such a high drift rate can, therefore, be regarded as an ‘extreme’ assumption.

The influence of the volatility is also considerable, as it broadens the range of possible results significantly and the degree of uncertainty for the decision-maker increases accordingly. In this study, the volatility is defined as the factor σ that is applied to the standard deviation in the GBM as displayed in eq. (3-10) in section 3.5.4.1.

Table 6-11 comprises the results for the base ELV increasing investment scenario in the savings and the losses perspective as well as the delta of both perspectives. It shows that both the drift rate and the volatility of the GBM influence the ROV, but the influence of the drift rate is considerably higher. The delta between the savings and the losses perspective is comparably low, as to be expected based on the discussions in 5.4. Therefore, in the following, only the savings perspective will be assessed in order to reduce the number of results.

Table 6-11: Results of the increasing investment standard scenario, base ELV [σ: volatility of the GBM, μ: drift rate of the GBM, ROV: real option value in M€, R: return in % of the investment in t_0, invest: number of paths recommending an immediate investment].

		Savings perspective			Losses perspective			Delta	
σ	μ	ROV	R	Invest	ROV	R	Invest	ROV	Invest
0.01	0.04	0	0.00%	0	0	0.00%	0	0	0
0.05	0.04	0.094	0.19%	6 184	0.092	0.18%	6 117	0.002	67
0.01	0.08	0.590	1.18%	84 427	0.584	1.17%	84 186	0.006	241
0.05	0.08	0.914	1.83%	40 941	0.907	1.82%	40 833	0.007	108
0.01	0.12	2.705	5.42%	100 000	2.705	5.42%	100 000	0	0
0.05	0.12	2.750	5.51%	80 447	2.745	5.50%	80 419	0.005	28
0.01	0.16	4.936	9.88%	100 000	4.936	9.88%	100 000	0	0
0.05	0.16	4.940	9.89%	96 078	4.939	9.89%	96 076	0.002	2

Table 6-12 displays the results for the standard and high consumable costs scenario for both, base and tight ELV. It shows that a higher NO_X reduction (i.e. higher total investment and operating costs) leads to higher option values whereas the influence of the consumable costs is comparably low. Even though the scenario assumes double consumable costs, the option values decline only slightly.

The results further highlight that a strong increase (i.e. drift rate) of the investment is necessary, in order to make an early investment favorable. If a return R of 3 % is expected by the decision-maker (which is 1.5 M€) for the EU base ELV SCR, the drift rate needs to be 10 %, whereas a return of 6 % (3 M€) already requires a drift rate of about 13 %. An annual average increase of the investment by 10-13 % based on market properties only can be considered unlikely in most parts of the world. Therefore, there is a clear need for political intervention, if early investments shall be promoted.

Table 6-12: Results of the increasing investment scenario, savings perspective [base: base ELV (80mg/Nm³), tight: tight ELV (40 mg/Nm³)].

		Base			Tight		
σ	μ	ROV	R	Invest	ROV	R	Invest
Standard							
0.01	0.04	0	0.00%	0	0	0.00%	0
0.05	0.04	0.094	0.19%	6 184	0.102	0.18%	5 888
0.01	0.08	0.590	1.18%	84 427	0.639	1.11%	82 300
0.05	0.08	0.914	1.83%	40 941	1.027	1.78%	40 016
0.01	0.12	2.705	5.42%	100 000	3.078	5.34%	100 000
0.05	0.12	2.750	5.51%	80 447	3.133	5.44%	79 916
0.01	0.16	4.936	9.88%	100 000	5.658	9.82%	100 000
0.05	0.16	4.940	9.89%	96 078	5.663	9.83%	95 929
High consumable costs							
0.01	0.04	0	0.00%	0	0	0.00%	0
0.05	0.04	0.064	0.13%	4 365	0.066	0.11%	3 891
0.01	0.08	0.368	0.74%	67 437	0.355	0.62%	60 464
0.05	0.08	0.755	1.51%	35 232	0.819	1.42%	33 548
0.01	0.12	2.435	4.87%	100 000	2.717	4.72%	100 000
0.05	0.12	2.501	5.01%	76 783	2.802	4.86%	75 610
0.01	0.16	4.666	9.34%	100 000	5.296	9.19%	100 000
0.05	0.16	4.674	9.36%	95 027	5.307	9.21%	94 701

The situation changes if direct fees on NO_X emissions are considered. The results in Table 6-13 display that depending on the initial NO_X fee in Euro per ton of NO_X emitted, no or only a very low drift rate of the investment is necessary in order to achieve a considerable ROV. For the EU SCR base ELV, NO_X fees of 3 130 €/t and more lead to a return above 5 % (i.e. an ROV of more than 2.5) if the drift rate of the investment is 0.[10]

[10] For the NO_X fees, the inflation rate of 1.5 % is considered and the volatility of the investment GBM is 0.05.

Table 6-13: Results of the increasing investment scenario, savings perspective considering NO_X fees.

		Base			Tight		
σ	μ	ROV	R	ROV	R	ROV	R
1 000 €/t							
0.05	0.00	0.060	0.12%	4 418	0.049	0.09%	3 188
0.05	0.02	0.261	0.52%	15 683	0.233	0.40%	12 611
0.05	0.04	0.739	1.48%	36 105	0.714	1.24%	31 461
2 000 €/t							
0.05	0.00	0.674	1.35%	35 473	0.538	0.93%	26 589
0.05	0.02	1.399	2.80%	58 892	1.260	2.19%	49 634
0.05	0.04	2.315	4.63%	77 379	2.257	3.92%	70 910
4 000 €/t							
0.05	0.00	4.142	8.29%	95 903	3.969	6.89%	92 023
0.05	0.02	5.117	10.24%	98 386	5.087	8.83%	96 581
0.05	0.04	6.116	12.24%	99 452	6.238	10.83%	98 700
8 000 €/t							
0.05	0.00	11.758	23.54%	100 000	11.981	20.80%	100 000
0.05	0.02	12.737	25.50%	100 000	13.111	22.76%	100 000
0.05	0.04	13.737	27.50%	100 000	14.263	24.76%	100 000

For the NPV calculation, the NO_X fees are considered before and after the installation of the plant, with the corresponding emission levels, as they need to be paid from the time they come into force, no matter if emissions are technically abated or not. Therefore, the number of periods considered increases with a delayed investment (due to the fixed lifetime contemplation). As discussed already, this may not always be a realistic contemplation. Yet, the calculations can easily be adapted to the fixed end of life contemplation if applicable. An example will be provided as sensitivity analysis in section 6.5.2.

6.4.1.2 NOx Market

The NO_X market scenario has several similarities with the NO_X fees scenario. Again, annual costs based on the amount of NO_X emitted are considered. The main difference is that the NO_X price is not deterministic, but stochastically simulated. Again, a GBM is assumed with drift rate μ_{NOx} and volatility σ_{NOx}. For a volatility 0 and a drift rate of 1.5 %, the results of the NO_X market calculation equal those of the NO_X fee calculation considering inflation. For the NO_X market, the inflation rate is not additionally considered but part of the assumed drift rate of the GBM. Furthermore, a different set of random numbers is used for the calculation in order to avoid a direct correlation between the simulated investment and the NO_X price.

For the calculations displayed in Table 6-14, the drift rates are assumed rather high (5 % and 10 %). This is considered reasonable, as a well-designed cap-and-trade system (or any other certificate trading system) aims at a shortage of certificates that leads to significantly rising prices over time.

The results display a strong dependency of the ROV of the initial price and the drift rate, whereas the volatility has hardly any influence. This is caused by the nature of the decision that aims at comparing earlier with later investments. Therefore, the price development in later periods (after the decision-making period) does hardly affect the decision, as it is the same for both the early and the late investment. Only the prices in the last periods (in the fixed lifetime contemplation) and the first periods affect the decision.

Furthermore, the results display higher option values for the base ELV case compared to the tight ELV case, as the shares of investment and operating costs are lower compared to the share of NO_X costs. The NO_X costs in the last periods are higher (compared to the tight case), due to the higher amount of NO_X emitted per period after the investment.

Table 6-14: Results of the NOx market scenario, savings perspective, the investment is assumed to remain constant (volatility and drift are 0).

		Base			Tight		
σ_{NOx}	μ_{NOx}	ROV	R	Invest	ROV	R	Invest
1 000 €/t							
0.05	0.05	0.001	0.00%	365	0	0.00%	0
0.10	0.05	0.034	0.07%	6 262	0	0.00%	77
0.05	0.10	1.182	2.37%	96 287	0.013	0.02%	5 456
0.10	0.10	1.287	2.58%	76 080	0.118	0.20%	16 488
2 000 €/t							
0.05	0.05	1.554	3.11%	100 000	0.563	0.98%	99 346
0.10	0.05	1.554	3.11%	96 351	0.569	0.99%	82 051
0.05	0.10	5.827	11.67%	100 000	2.702	4.69%	100 000
0.10	0.10	5.828	11.67%	99 996	2.702	4.69%	99 917
4 000 €/t							
0.05	0.05	6.585	13.18%	100 000	5.186	9.00%	100 000
0.10	0.05	6.586	13.19%	100 000	5.186	9.00%	100 000
0.05	0.10	15.131	30.29%	100 000	9.464	16.43%	100 000
0.10	0.10	15.134	30.30%	100 000	9.465	16.43%	100 000

6.4.1.3 Discontinued Subsidies

The discontinued subsidies scenario assumes a jump of the investment in a future period with a certain probability p. This scenario refers to the discontinuation of an investment support program that lowers the investment expenditures for the investor in the present and may lead to a jump in the future when discontinued. For simplicity, the height of the jump h is calculated as a percentage of the investment in t_0. In practice, many programs refer to the actual investment at time *t*, i.e. the incentive payment is calculated as a percentage of the total investment expenditures. The difference, however, can be assumed low with regard to the general implications of this scenario. Furthermore, the jump is not discounted. There is only one jump allowed during the decision-making period. For real world applications, the details of the underlying program can be considered in the calculation design. Further assumptions mentioned above can be adapted accordingly.

The results of the example at hand are displayed in Table 6-15. It assumes a volatility of the investment of 0.05 and a drift rate of the investment of 0.015, which corresponds to the inflation rate of the examples above. For a volatility and drift of 0 (as assumed in the NO_X fees scenario), the degree of uncertainty is low and therefore, the option values are low, too. Hence, high subsidies of 30 % or more (as a share of the initial investment) are necessary, in order to get a (low) positive ROV. In order to get a reasonable return, the subsidies have to be even higher, which is not considered feasible for actual applications. Therefore, the volatility of 5 % and the drift rate of 1.5 % are assumed.

The results show comparably low option values. This leads to the conclusion that for a direct impact on the timing of investment decisions, the threshold of the incentive to be paid is comparably high. A support of 30 % of the total investment is the minimum value in the given example in order to achieve an acceptable return for an early investment.[11] Furthermore, the sooner the program ends, i.e. the sooner the jump is likely to occur, the higher the option values. This result clearly supports the statement of Dixit and Pindyck (1994, p. 309): "*(…) if a government wishes to accelerate investment, the best thing it can do is to enact a tax credit right away, threaten to remove it soon, and swear never to restore it (…)*".

A combination of an investment support scheme with an additional policy instrument such as e.g. NO_X fees may hence be a promising approach in order to achieve the goal of early investments as displayed in Table 6-16 for the base ELV example with a NO_X fee of 500 and 1 000 €/t.

[11] This issue is further aggravated by the fact that technical improvement may lead to decreasing investments in the future. In such cases, a direct monetary incentive is even less effective than assessed above.

Table 6-15: Results of the discontinued subsidies scenario, savings perspective, volatility 0.05, drift rate 0.015 [h: height of the jump, p_i: probability of the jump at time i].

	Base			Tight		
h	ROV	R	ROV	R	ROV	R
p_0=0 %, p_1=25 %, p_2=25 %, p_3=25 %, p_4=25 %						
10%	0.078	0.16%	4 521	0.084	0.15%	4 253
20%	0.379	0.76%	13 081	0.419	0.73%	12 633
30%	1.047	2.10%	22 274	1.174	2.04%	21 814
p_0=0 %, p_1=100 %, p_2=0 %, p_3=0 %, p_4=0 %						
10%	0.210	0.42%	10 052	0.228	0.40%	9 490
20%	1.317	2.64%	37 733	1.457	2.53%	36 562
30%	3.934	7.88%	70 846	4.413	7.66%	69 754
p_0=0 %, p_1=50 %, p_2=25 %, p_3=15 %, p_4=10 %						
10%	0.125	0.25%	6 517	0.136	0.24%	6 151
20%	0.698	1.40%	21 826	0.771	1.34%	21 155
30%	2.019	4.04%	39 200	2.264	3.93%	38 526

Table 6-16: Results of the discontinued subsidies scenario considering emission fees, savings perspective, base ELV, volatility 0.05, drift rate 0.015.

	500 €/t			1 000 €/t		
h	ROV	R	Invest	ROV	R	Invest
p_0=0 %, p_1=25 %, p_2=25 %, p_3=25 %, p_4=25 %						
10%	0.266	0.53%	13 441	0.688	1.38%	29 567
20%	0.855	1.71%	25 117	1.573	3.15%	39 817
30%	1.785	3.57%	32 119	2.655	5.32%	42 902
p_0=0 %, p_1=100 %, p_2=0 %, p_3=0 %, p_4=0 %						
10%	0.688	1.38%	27 247	1.698	3.40%	54 226
20%	2.887	5.78%	64 695	5.071	10.15%	86 773
30%	6.546	13.11%	89 562	9.355	18.73%	97 825
p_0=0 %, p_1=50 %, p_2=25 %, p_3=15 %, p_4=10 %						
10%	0.415	0.83%	18 540	1.043	2.09%	38 779
20%	1.549	3.10%	39 418	2.766	5.54%	56 961
30%	3.389	6.78%	52 556	4.914	9.84%	62 765

6.4.2 European Plant SNCR

The results for the SNCR installation in the EU plant will be primarily assessed in comparison to those of the SCR installation. The deterministic results of the techno-economic model displayed already that the total investments and operating costs are lower, but the share of investments compared to the operating costs is comparable to the SCR installation. Therefore, the return can be expected to be in a similar range. This is confirmed by the results displayed in Figure 6-2.

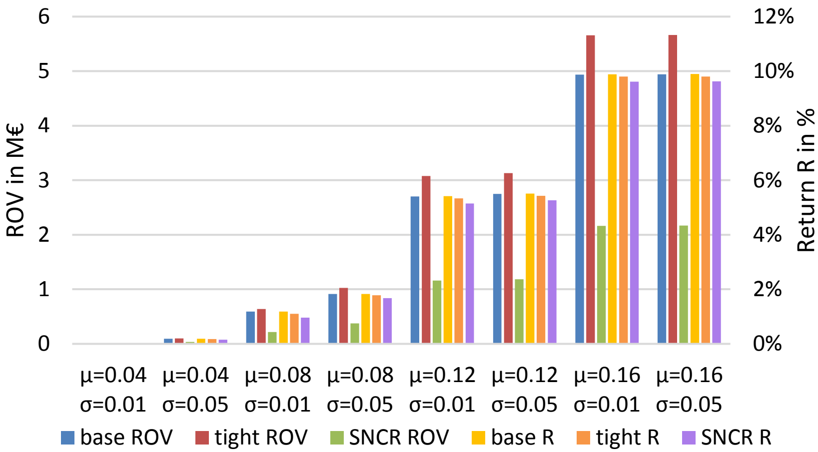

Figure 6-2: A comparison of the ROV and return (R) of the EU-SNCR case study with the base- and tight-ELV studies of the EU-SCR example in the increasing investment scenario.

The figure displays the ROV and the returns R of the SCR for the base and the tight ELV and the SNCR in the increasing investment scenario. While the ROV of the SNCR are about half the ROV of the SCR examples, the returns are approximately the same. This suits the expectations, as the lower total investment and operating costs require a lower absolute ROV in order to influence the decision. As the investments and operating costs are about half those of the SCR examples, the ROV results confirm the expectation, that the decision-making in the increasing investment scenario without consideration of NO_X fees or other policy instruments is comparable in all three EU examples. The detailed results for the EU SNCR example (as for all other examples) are provided in Annex B.

Figure 6-3 displays the results for the increasing investment SNCR example, under consideration of NO_X fees. The ROV and the number of paths are displayed against the NO_X fee in Euro per ton of NO_X emitted.

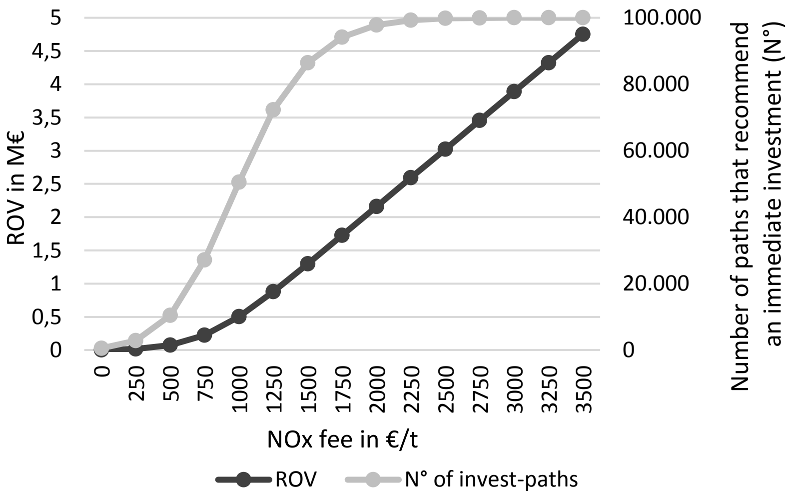

Figure 6-3: The ROV and the number of paths that recommend an immediate investment over the NOx fee in €/t. (The volatility of the investment is assumed to be 0.05 with a drift rate of 0.015).

While the ROV increases rather linearly above a threshold fee of about 1 000 €/t, the number of paths that recommend an immediate investment increases according to an S-shaped curve. A rapidly increasing number of paths in the money reduces the risk of not achieving any savings by advancing the investment. This follows the intuition, as the NO_X fee is assumed to be deterministically predefined. Therefore, the uncertainty and particularly the downside risk is comparably low in this setting.

In total, the real option values for the SNCR NO_X fees scenario are not only higher in the relative comparison of the return R, but also in absolute numbers (compared to the EU SCR examples). Therefore, the influence of NO_X fees on the overall decision-making is stronger, i.e. a lower specific fee may be able to change the investment decision. This is due to the higher total emissions that are emitted in the SNCR example after installation of the abatement technique.

For the NO_X market scenario, this conclusion applies accordingly. Regarding the example of an initial NO_X fee of 2 000 Euro per ton, the ROV for a volatility and drift rate of the NO_X price of 0.05 is 4.120. In case of volatility and drift of 0.1, the ROV is 12.131.[12] Hence, again, the ROV is not only higher in the relative comparison based on the return, but also in an absolute manner.[13]

In contrast to the instruments that target the amount of NO_X emitted by implementing fees or other sorts of direct emission related payments, the instrument of discontinued investment related subsidies has a lower impact on SNCR investments, due to the lower initial investment. For jump heights of 10 %, 20 % and 30 % and a jump probability of 100 % in period 1, the ROV for the EU SNCR example are 0.079, 0.052 and 1.629.[14] Therefore, the ROV are not only absolutely lower but also regarding their return R (based on equal assumptions).

---

12 All other parameters are assumed equal to the SCR calculation in Table 6-14.

13 The EU-SCR results for drift and volatility 0.05 are 0.563 and 1.554, for drift and volatility 0.1 they are 5.828 and 2.702.

14 Assuming a drift rate of 0.015 and a volatility of 0.05 as for the SCR example.

6.4.3 Indian Plant

The Indian plant is primarily characterized by the higher share of operating costs and NO_X fees (if applicable). Due to the higher initial emissions and the higher total amount of emissions to be abated, the reagent costs increase significantly. This affects most of the scenarios considered in this work. While purely investment related scenarios have a lower impact on these installations, the NO_X fees and NO_X market scenarios lead to high impacts and, hence, high real option values. Several selected results will be presented in the following, all of them in comparison with the three EU examples.

Figure 6-4 displays the results of the increasing investment scenario. Compared to the EU examples, both the ROV and R of the Indian examples are lower, due to the 'buffering' effect of the high operating costs. In total, the incentive for an early investment caused only by increasing investments is comparably low for the Indian case. Up to a drift rate of 12 %, the expected return of an early investment is below 5 %, for a drift rate below 8 % it is hardly more than 1 %. Therefore, in a realistic setting, that does not assume extraordinary high drift rates for the investment GBM, an Indian plant operator cannot be expected to advance the investment if no additional policy measures are in force.

For the increasing investment scenario with NO_X fees, the effect is vice versa. Due to the higher amount of NO_X emitted before and after the installation of a control system, the impact of a NO_X fee is a lot higher as displayed in Figure 6-5. This effect needs to be kept in mind when designing policy instruments. If the technical standards of the installations in a country differ significantly, a fixed fee without allowances may endanger the profitability of one plant, whereas it hardly affects a different plant. This may also lead to a preference for certain types of fuels and therefore interact with policy measures on e.g. climate issues.

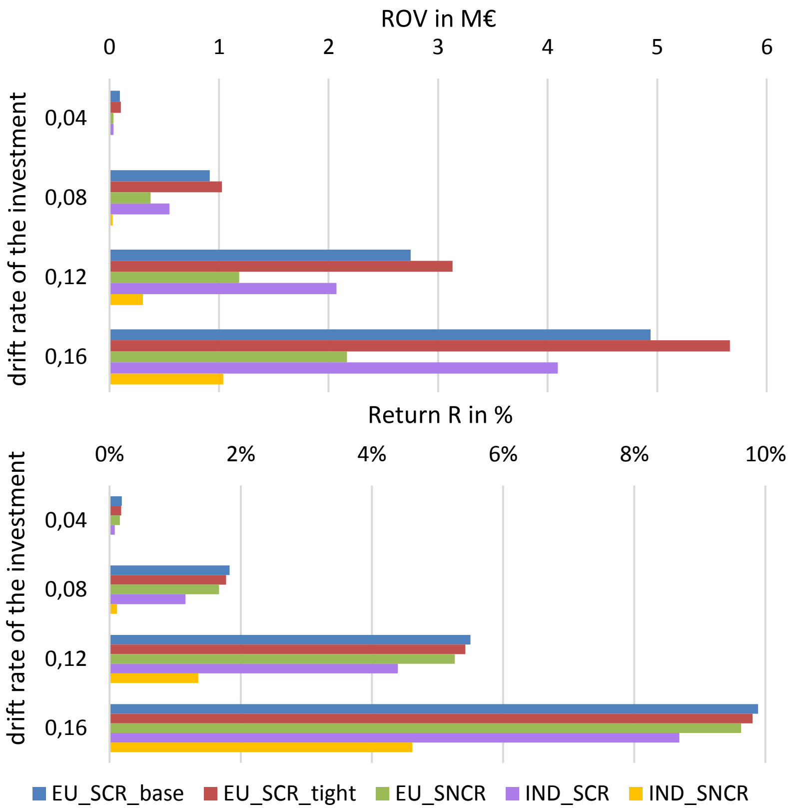

Figure 6-4: ROV and return of all installations for the increasing investment scenario with different drift rates and a volatility of 0.05.

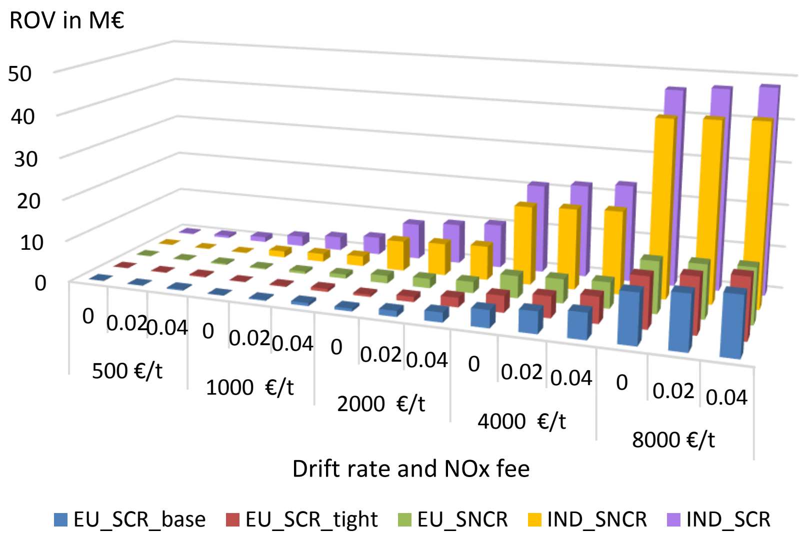

Figure 6-5: A comparison of the ROV of all installations for the increasing investment NO_X fee scenario with different drift rates and specific NO_X fees.

As for the increasing investment scenario, the discontinued subsidies scenario achieves only low real option values without consideration of NO_X fees. For the investigated range of jump probabilities and jump heights (max. 30 %), the highest R achieved for the Indian plant is 5.2 %. Therefore, a support scheme as a stand-alone incentive for early investments is in this context rather unattractive.

In combination with NO_X fees, the situation changes, as displayed in Figure 6-6. It shows that the ROV reacts not only very volatile towards the NO_X fee but also towards the different probability assignments. In all three assignments, the total probability is one, therefore, the jump is assumed to happen in any case and only the probability for the time of occurrence differs. Nevertheless, the influence of the time of the jump on the total ROV is apparent. This shows that political ambiguity influences decision-making not only with regard to the measures and policy instruments to be implemented but also by the timing and run-time of such measures. But not only the characteristics of the actual measures that may be implemented are relevant, but also the expectation among industrial decision-makers if no reliable information is available.

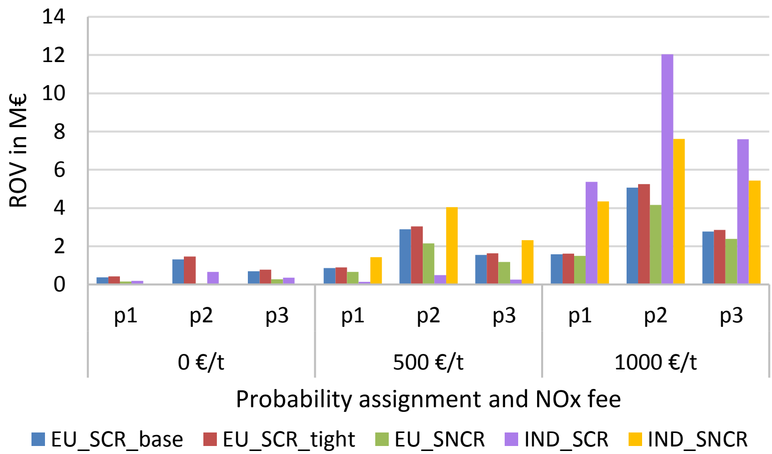

Figure 6-6: Results of the discontinued subsidies scenario considering NO_X fees with jump height h = 20 % and the probability assignments:
p1: p_0=0 %, p_1=25 %, p_2=25 %, p_3=25 %, p_4=25 %,
p2: p_0=0 %, p_1=100 %, p_2=0 %, p_3=0 %, p_4=0 %,
p3: p_0=0 %, p_1=50 %, p_2=25 %, p_3=15 %, p_4=10 %.

An eligible criticism regarding the Indian case study is that the inflation rate has not been adapted. The average annual inflation rate in India over the last 10 years varied between 3.6 % and 11 % (IMF 2018). Nevertheless, the use of the EU inflation rate was assumed reasonable in order to allow for direct comparisons among the examples. The influence of the inflation rate on the overall results will be discussed in the context of the sensitivity analyses in section 6.5.2.

A further scenario that could be investigated in this context is the variation of operating costs as they have a significant impact on the total NPV and hence the ROV. As the availability of data is very limited, however, this is not part of this work. If a user possesses better data, a scenario with variable operating costs can easily be implemented, following e.g. the example of the NO_X market scenario. The most critical influencing parameter to this regard is the price of the reagent, which causes the majority of operating costs in the Indian examples.

6.5 Decision-Making

This section aims at investigating strategies for industrial decision-makers in order to analyze the results of the calculations above. Therefore, a brief overview of further possible contemplations is provided as well as a short summary of influencing parameters in the framework of sensitivity analyses.

6.5.1 Further Contemplations

Due to the vast amount of results that are already available for the case studies at hand, it goes beyond the scope of this work, to assess possible further contemplations in detail. What shall be mentioned is that the tables in Annex B display not only the ROV and return, but also the number of paths that recommend an immediate investment. This number is not directly related to the ROV, as the ROV is influenced by the level of uncertainty. The higher the uncertainty, the higher the ROV, as paths with a positive development may achieve very high ROV while the downside risk is cut off. Therefore, a smaller total number of paths in the money is necessary, in order to achieve a certain ROV than in a case with a lower level of uncertainty.

This aspect is recommended to be integrated into industrial decision-making. It is directly related to the risk perception of the decision-maker or decision-making board. For industrial entities, the risk perception may not only depend on the personal attitude of the decision-maker(s), but also on the economic situation and the culture of the company. As discussed in section 3.4.4, the different approaches of decision theory may support a rational decision-making in any case.

One example of a comparably high option value with a rather low number of paths that recommend an immediate investment is the Indian SCR installation in the discontinued subsidies with emission fees scenario. For a NO_X fee of 500 €/t, the probability setting p2 (i.e. 100 % probability for a jump in t_1) and a jump height of 30 %, the ROV is 1.997 and the resulting R is 4 %, which is a considerable average saving for an early investment. The number of paths that recommend an early investment, however, is 48 019 and hence less than 50 %.

Furthermore, the losses perspective allows for investigating the mean and maximum losses of a certain scenario. The results for the initial example, the EU SCR base ELV in the increasing investment scenario are displayed in Table 6-17. It shows that the mean losses hardly depend on the volatility, whereas the maximum losses differ massively. Furthermore, in particular in the cases of high volatility, the 98-percentile is a lot lower than the maximum loss. Depending on the drift rate, it can be less than half the amount of the maximum loss. This accounts for the unlikeliness of the maximum losses case. It is possible but very unlikely that such losses occur.

It is again to be mentioned that this is a worst-case contemplation, which should not be over-emphasized during decision-making, as it does not account for any rational strategy. It displays the maximum possible losses if the worst case occurs.

Table 6-17: Mean, maximum and 98-percentile losses in M€ of the losses perspective for the increasing investment scenario of the EU SCR base ELV.

	Volatility 0.01				Volatility 0.05			
	t_1	t_2	t_3	t_4	t_1	t_2	t_3	t_4
Drift rate: 0.04								
Mean losses	0.00	0.00	0.00	0.00	0.44	0.46	0.45	0.45
Maximum losses	0.79	0.05	0.00	0.00	10.96	13.53	17.84	22.06
98-percentile	0.00	0.00	0.00	0.00	3.89	4.92	5.55	6.04
Drift rate: 0.08								
Mean losses	0.60	1.35	2.34	3.57	1.35	2.29	3.34	4.56
Maximum losses	2.94	4.54	6.67	9.04	13.52	19.15	27.23	35.87
98-percentile	1.65	2.96	4.43	6.11	6.17	9.82	13.37	17.08
Drift rate: 0.12								
Mean losses	2.70	5.94	9.74	14.17	2.92	6.05	9.79	14.19
Maximum losses	5.18	9.41	14.63	20.59	16.20	25.24	37.81	52.08
98- percentile	3.84	7.70	12.11	17.16	8.55	15.13	22.18	30.02
Drift rate: 0.16								
Mean losses	4.94	10.92	18.10	26.62	4.97	10.91	18.08	26.60
Maximum losses	7.52	14.68	23.61	34.15	18.98	31.83	49.74	71.10
98-percentile	6.12	12.83	20.76	30.12	11.02	20.88	32.12	45.22

6.5.2 Influencing Parameters and Sensitivity Analyses

Table 6-18 displays an overview of parameters that have not been varied in the case studies above and discusses their influence on the ROV in general and quantitatively with regard to the EU-SCR base ELV increasing investment scenario. It displays a major impact of the interest rate on the ROV and hence the decision. While the ROV in the reference scenario is 2.75, it drops to 0.30 if the interest rate doubles. In this case, the decision may switch from an immediate investment to a deferral of the investment.

Table 6-18: Parameters not investigated in the case studies above with their influence on the ROV. The reference case is the EU SCR base ELV increasing investment scenario with volatility 0.05 and drift rate 0.12. The ROV in the reference case is 2.750.

Parameter	Explanation	Base value	New value	New ROV
Temporal aspects				
Lifetime	Impact depends on the considered scenario. If uncertainty is investment related, ROV can be expected to decrease with increasing lifetime.	20 a	30 a	2.550
Decision-making time	Impact depends on the considered scenario, i.e. the underlying stochastic process.	5 a	3 a	2.784
Fixed end of life (*fel*) instead of fixed lifetime (*flt*)	ROV is lower in case of fixed end of life contemplation.	*flt*	*fel*	1.447
Monetary aspects				
Interest rate	ROV decreases with increasing interest rate	3 %	6 %	0.300
Inflation rate	ROV increases with increasing inflation rate	1.5 %	3 %	3.247

The shift to the fixed end of life contemplation has the second biggest impact in the given case. This is caused by the number of periods considered, which decreases in case of a later investment. Therefore, the NPV of a later investment decreases, as the operating costs have to be paid for fewer periods. If considerable emission fees have to be paid before the installation of the system, the advantage of early investments decreases.

The impact of the inflation rate is also considerable, but lower than that of the interest rate. Furthermore, the inflation rate is in many parts of the world less volatile than the interest rate, so that the impact can be expected lower. In unstable economies, however, this issue may also play a major role.

The impacts of the lifetime and the decision-making time are the lowest and they are not expected to play a significant role unless the considered setting assumes ‘extreme’ values, such as very short lifetimes.

For scenarios that consider NO_X fees, the general impact of the parameters is comparable, unless stated otherwise, as for the switch of the lifetime contemplations. For scenarios that focus on an uncertain future development of operating costs, the effects may vary, as mentioned above. A comparison of the quantitative impact with regard to the given example is displayed in Figure 6-7.

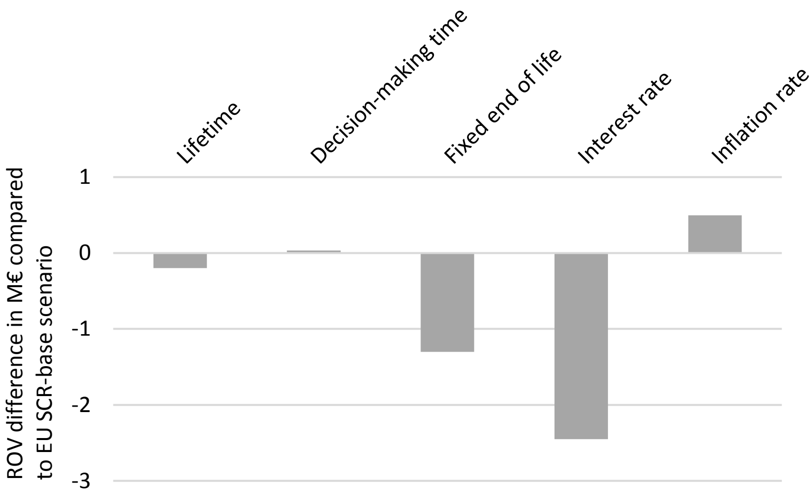

Figure 6-7: Deviations of the ROV for the sensitivity examples. The underlying data is displayed in Table 6-18.

A further aspect to be mentioned in the context of further assessments is the monetary impact of NO_X fees in relation to CO_2 emission costs for a plant operator. The EU plant emits a total amount of approximately 2.57 million tons of CO_2 per year.[15] The amount of NO_X emitted without abatement is 2 107 tons per year and the annual emissions of the base ELV SCR example are 843 tons. Hence, the total NO_X emissions are about the order 10^3 lower compared to the CO_2 emissions. Therefore, NO_X emission fees would have to be about the same factor higher in order to cause comparable costs for the plant.[16]

Regarding the cross-media effect caused by the SCR, the electricity consumption can be converted into CO_2 emissions in order to account for the additional costs directly caused by the installation. For the electricity consumption in the EU SCR base ELV case (11 753 MWh per year), a total amount of additional CO_2 emissions of 9 153 tons per year results. Assuming a CO_2 price of 20 Euro per ton,[17] total annual CO_2 emission costs of 183 060 Euro result. This leads to an increase in the total operating costs of the SCR by about 9 % (from about 2.06 M€ to 2.24 M€). Therefore, depending on the price of CO_2, it is recommended to consider the cross-media costs when evaluating a NO_X abatement installation. Within the study level accuracy of +/- 25 %, however, the costs of CO_2 emissions are usually not one of the most important contributors leading to significantly differing results, particularly when assessing plants in developing or emerging countries that may not yet have any CO_2 fees implemented.[18]

15 The calculation assumes complete combustion, i.e. the total amount of C present in the fuel (67.69 mass-% absolute) is completely converted into CO_2.

16 This example does not consider any allowances or other non-linearity with regard to the design of the policy instrument.

17 This is the approximate price in October 2018 according to European Energy Exchange AG (2018).

18 This contemplation considers only the direct cross-media effect caused by the electricity consumption and does not provide a full assessment of effects such as an LCA analysis.

6.6 Policy Implications

This section aims at summarizing the most relevant policy implications, which can be derived from the results above. It is not possible to develop distinct recommendations for policy-makers all over the world, as the legal and economic situation in different regions and markets differs a lot. Nevertheless, it is possible to identify the key drivers and influencing parameters for decision-makers with regard to the investment timing, based on the results presented above. The implications derived below are based on the assumption, that decision-makers act rationally and consider real options theory for their decision-making.

The first subsection investigates policy implications that are directly related to the case study and scenario results at hand, i.e. the example of NO_X abatement in LCP. The second subsection targets the broader picture and analyzes general impacts that result from real option thinking in the context of environmental investments. This section does not provide a list of implications that is valid for all sorts of applications but aims at delivering some thought-provoking impulses for future studies and case-specific investigations.

6.6.1 Implications of the Scenario Results

The results of the case studies and scenarios presented in section 6.4 allow for several conclusions, particularly with regard to policy instruments. In order to evaluate the suitability of a policy instrument, it is important to assess and understand the share of investment, operating costs and the amount of NO_X emitted including the thereof resulting NO_X fees (if applicable) with regard to the total NPV of the project. The higher the share of a cost item, the more influence on the decision will result from market fluctuations or from a policy measure that targets this item. The shares of the cost items depend on the technical standards implemented in the plant, the ELV to be achieved, the price level of consumables and the market situation for equipment investments. The following list summarizes a few direct conclusions that result from the calculations above:

- Both the drift rate and the volatility influence the ROV, but the influence of the drift rate is considerably higher. If no policy measures are considered, a strong increase (i.e. drift rate) of the investment is necessary, in order to make an early investment favorable (in the given examples 10 % or more). Therefore, there is a clear need for policy intervention, if early investments shall be promoted.

- The situation changes if direct fees on NO_X emissions are considered. No, or only a very low drift rate of the investment is then necessary in order to achieve a considerable ROV for an immediate investment.[19] However, the economic situation and profitability of the plants have to be kept in mind when designing such instruments. If the technical standards of the installations in a country differ significantly, a fixed fee without allowances may endanger the profitability of one plant, whereas it hardly affects a different plant. It may also lead to a preference for certain types of fuels or techniques and therefore interact with policy measures on e.g. climate issues.

- For a NO_X market scenario, the results display a strong dependency of the ROV on the initial price and the drift rate of the NO_X price, whereas the volatility has a lower influence. Beyond that, the statements for deterministic NO_X fees apply accordingly.

- The results for the discontinued subsidies scenarios provide comparably low option values. For supporting immediate investment decisions, the threshold of the incentive to be paid is comparably high. A support of 30 % of the total investment is the minimum value in the

[19] The actual parameters of volatility and drift rate that are necessary to achieve a certain return depend primarily on the initial NO_X fee.

given example in order to achieve an acceptable return for an early investment. Even though the reference is rather old, this result is confirmed by Mooren et al. (1991). In the examples at hand, the sooner the program ends, i.e. the sooner the jump is likely to occur, the higher the option values. This result clearly supports the statement of Dixit and Pindyck (1994, p. 309) as already mentioned before: "*(…) if a government wishes to accelerate investment, the best thing it can do is to enact a tax credit right away, threaten to remove it soon, and swear never to restore it (…)*". A further conclusion thereof is that political ambiguity with regard to the timing and run-time of such measures influences decision-making. If no reliable information is available (i.e. in case of political ambiguity), the expectations among industrial decision-makers directly influence decision-making.

- A combination of an investment support scheme with an additional policy instrument such as e.g. NO_X fees may be a promising approach in order to achieve the goal of early investments. Yet such an interaction of policy measures still requires a temporal limitation of the support scheme in order to promote early investments.

- Depending on the actual setting of an installation, the operating costs may have a significant influence on the total NPV and hence the investment decision. Therefore, policy may not only consider influencing investments, but also operating costs, i.e. by supporting industries that provide consumables in the country/region in order to stabilize prices.

- Public funding of R&D activities may lead to delayed investments, if the investment expenditures for new or improved abatement techniques can be expected to decrease in the near future.

To conclude, two important statements shall be emphasized. As an investment can only be advanced by a more or less disruptive setting, an important conclusion for policy-makers is to implement fixed deadlines for all sorts of positive instruments, i.e. for instruments that lower the costs for investors, such as funding schemes. The implementation of long-term oriented funding schemes may sound reasonable at first sight, but with the political goal to advance investments, this analysis explains the need for a temporal limitation.

Furthermore, monetary instruments such as fees or taxes need to reach a certain threshold in order to promote early investments actively. Otherwise, the instruments may not be successful at all or lead to windfall gains for investors that decide to invest early for a differing reason such as e.g. publicity or customer requirements.

6.6.2 General Implications of Real Option Thinking on Environmental Investments

Beyond the specific policy conclusions of the case studies and scenarios above, a broader overview with conclusions based on the idea of real option thinking (as introduced in section 3.5.5) with regard to environmental investments in general (i.e. not limited to NO_X abatement) shall be provided in the following.

These implications are based on a qualitative assessment of possible effects, which does not claim completeness but aims at providing an overview of the most intuitive effects as a basis for further discussions. The assessment considers not only the deferral option but also the other two basic options, expansion and abandonment/switching option and puts them in a framework with the types of environmental investments introduced in section 3.1. In certain applications, specific issues might not be relevant or new aspects may have to be added. Not particularly option related aspects such as windfall gains, lock-in phenomena or rebound effects are not considered in the following.

The first part of this section describes possible impacts with regard to C&C policy while the second part discusses economic incentives. Complex and application-specific instruments such as voluntary agreements or deposit-refund systems are not considered due to the difficulty to draw general conclusions with regard to these instruments.

Generally, investment decision-making is influenced by several aspects of real option thinking. The consideration of the options themselves leads to a fundamental influence. While traditional investment decision-making methods focus on the profitability of the investment or on comparisons between different investment alternatives, the real options analysis includes the comparison of an investment with itself executed at a later time, in several steps, or its abandonment in case it is not (expected to be) successful.

Furthermore, the consideration of the real option value may influence the investment decision. The higher the option value, the higher its influence on the decision and the higher the level of uncertainty, the higher the option value, ceteris paribus (Götze et al. 2015). This leads to several implications, whereof distinct examples will be provided below.

6.6.2.1 Implications with Regard to Command and Control Methods

C&C regulation sets the scope of action for industrial decision-makers. While such regulation does not include any incentives to be better than the limit values,[20] it has the power to stop operation of a business and to close down plants, at least temporarily. Therefore, from a decision-maker's perspective, the room for optimization with regard to the regulation is limited. Nevertheless, it may open up three common options for plant operators:

[20] There may be exceptions, such as the top-runner program (cf. 2.3.1.1).

- New regulation usually includes an adaption period for existing plants, i.e. the plants have a certain amount of time to meet the regulation. This may open up deferral options. Decision-makers can decide whether to invest immediately or to delay the investment to a later time within this period.

- If decision-makers are uncertain about future regulation (i.e. due to upcoming elections, ongoing amendments of regulation, etc.) they can plan an investment that includes an expansion option to lower the additional investment if emission limit values will be tightened.

- They can switch the project, e.g. to a different abatement technology that is more likely to be able to cope with (potential) new regulation.

Due to their binding character, C&C methods have to be carefully selected and implemented. They need to be tight enough to achieve environmental goals while avoiding the closing of businesses due to lacking profitability. Especially in industrialized countries, the shutdown of industrial operation often leads to leakage effects, i.e. the relocation of businesses to foreign countries with less tight regulation. The bottom line thereof is an increase in total emissions and negative economic effects for the abandoned country. This effect and its impacts depend on the sector, market and company structure. Hence, it should be analyzed in detail before implementing or amending environmental regulation. Real option thinking may enforce this effect, as a systematic screening process and a quantitative evaluation of options could reveal alternative paths of action that were not considered before.

6.6.2.2 Implications with Regard to Economic Incentives

Policy instruments targeting economic incentives can influence different parameters of investment decisions, depending on the type of instrument and option considered. The most common examples are expenditures, revenues, liquidity, image and reputation (including employee satisfaction), technology and knowledge.

The tables below cannot provide whole lists of possible implications but summarize important examples. The implications may be clear recommendations in a certain direction, or may just depict possible developments, which can be desired or undesired. Staged investments, for example, may be advantageous, e.g. if they enable the continuation of production due to remaining liquidity. In other cases, a full investment at once may be aspired due to its positive environmental effect.

All recommendations are based on the assumption that policy measures aim at a maximum positive environmental effect. Other aims, such as maintaining economic competitiveness, are not considered in the following. The conclusions are very general and therefore not separated according to the types of environmental investments (cf. section 3.1). For mandatory investments, the general conclusions with regard to the deferral option have already been derived. For the other types of options, it is assumed that the mandatory investments offer options beyond the legally required installation. Otherwise, if there is only one type/size of investment that can be installed and that is legally required to be installed, the conclusions below are not reasonable as there is no more managerial flexibility.

6.6.2.2.1 Option to defer

The option to defer has been discussed in detail for mandatory investments. For efficiency and risk-reducing investments, which may be economically beneficial, a high level of uncertainty leads to a high option value, which, in case of economically beneficial investments, counteracts the execution of an investment. Therefore, two major implications can be derived for this option: either policy measures can aim at reducing the level of uncertainty in order to lower the option value, or specific temporary incentives can be implemented to support early investments. A more detailed analysis of implications is provided in Table 6-19 for efficiency and risk-reducing investments, assuming that they can become economically beneficial.

Table 6-19: Impacts of deferral options on the most relevant economic incentive instruments.

Instrument	Implications
Pollution or product charges, taxes, and fees	• Unclear political situation supports deferral. • Long-term predictability may support/advance investments. • Amount of fees needs to be high enough to "compensate" uncertainties and support early investments.
Subsidies for environmentally friendly activities	• Long-term predictability may support/advance investments in case of recurring subsidies. • Runtime of investment programs should be limited to support early investments. • Volume of subsidies needs to be high enough to compensate uncertainties or economic disadvantages (to avoid deferral).
Removal of harmful subsidies	• May lead to fast environmentally harmful investments (before removal of investment programs), hence short announcement times are favorable. • May advance environmentally friendly investments if recurring subsidies for harmful techniques are cut back.
Tradable permits	• Permit prices need to be somehow predictable to advance investments. High uncertainty may support deferral. • Volume of payments needs to be high enough to create an economic need for investment.
Liability	• May advance investments if political regulation is clear and stable.
Information provision	• Possibility to benchmark may advance investments in low performing plants. • Awareness raising for staff, customers, stakeholders, and share-holders may advance investments.

6.6.2.2.2 Option to expand/contract

Table 6-20 displays implications of expansion options with regard to all three categories of investments. Formally, expansion and contraction options are closely related. Considering environmental investments, however, contraction options seem hardly relevant, as environmental regulation tends to become tighter all over the world. Therefore, new investments or add-ons for existing installations are necessary to abate more emissions. The contraction of the production itself may be possible because of environmental regulation. Yet, due to the focus on environmental investments, this option shall not be considered in the following. In general, expansion options have the most technical limitations. Therefore, this type of options requires a detailed technical understanding of the considered application in order to derive realistic conclusions.

Table 6-20: Impacts of expansion options on the most relevant economic incentive instruments.

Instrument	Implications
Pollution or product charges, taxes, and fees	• Uncertainty may support expansion options (in order to enable a reaction to tightening regulation). • Amount of payments needs to be high enough to compensate additional costs for expansion option (e.g. higher installation costs to prepare the piping for a later add-on). • Staged investment may be used to lower the technical risk of a change in production technology. • High fees promote full investment at once (no staged investment).
Subsidies for environmentally friendly activities Removal of harmful subsidies	• Support the expansion of environmentally friendly technology (beyond emission limit values). • Support the direct adjustment of the whole/large parts of the production (may avoid staged investments).
Tradable permits	• Uncertainty about future prices supports consideration of expansion options (if prices are not yet high enough to support the full investment, but to justify an expansion option). • Amount of payments needs to be high enough to compensate additional costs for expansion option (e.g. higher installation costs to prepare the piping for a later add-on). • Low prices and difficult forecasts may lead to staged investments.
Liability	• May avoid staged investments in order to lower the risk of liability issues.
Information provision	• Staff and stakeholders may support staged investments due to the possibility to adapt to and learn about the new technology step by step. • Staff and stakeholders may promote full investment in order to achieve the maximum environmental effect immediately.

6.6.2.2.3 Option to abandon/switch

With regard to environmental investments, the switching option can be considered more relevant than the abandonment option (cf. Table 6-21). As environmental regulation tends to be tightened all over the world, the abandonment of environmental investments seems rather unlikely. The switching option, hence, appears reasonable, if alternative techniques exist. Thus, in the given context, the switching option is closely related to the expansion option.

Table 6-21: Impacts of abandonment/switching options on the most relevant economic incentive instruments.

Instrument	Implications
Pollution or product charges, taxes, and fees	• High payments may endanger liquidity for environmental investment (risk of abandonment). • Switch to similar but less environmentally regulated products is promoted. • May support switch to environmentally (more) friendly alternative.
Subsidies for environmentally friendly activities Removal of harmful subsidies	• May encourage the switch to environmentally (more) friendly technology, hence long-term reliability should be aspired. • Volume of subsidies needs to be high/low enough to reach the break-even-point of the environmentally (more) friendly alternative.
Tradable permits	• Uncertainty about future prices supports consideration of abandonment/switching options (increasing option value). • (Constantly) low prices may lead to abandonment of efficiency investment (low economic incentive). • (Constantly) high prices may encourage the switch to environmentally (more) friendly technology.
Liability	• May encourage the switch to environmentally (more) friendly technology. • Abandonment of environmental investments due to liability issues is considered unlikely.
Information provision	• Awareness raising for staff, customers and shareholders may encourage switch to environmentally (more) friendly technology. • Abandonment of environmental investments may be counteracted by staff, trade unions, and shareholders.

The most critical impact that may result from the consideration of the abandonment option is again the aspect of emission leakage. The option to abandon industrial operation or parts thereof presumably leads to some sort of leakage effect.[21] It is again not considered in Table 6-21, but needs to be kept in mind when designing environmental regulation.

[21] Either the company itself relocates its production or competitors in the market can take over the delivery of existing customers.

7 Conclusions and Discussion

After the presentation of the case study results and their policy implications in chapter 6, a final validation, discussion and critical acclaim of the work at hand is provided in the following. A summary of the developed models and their outcomes and an outlook with ideas for future studies will conclude this work.

7.1 Validation

A validation of the work at hand is difficult, due to the vast amount of data that is necessary, particularly for the techno-economic model. Therefore, it is not possible, to compare the results of the model in this study directly with the results of other calculation tools such as the tool of the US EPA. However, several sub-components, such as the calculation of the catalyst volume described in section 4.4.2.1 can be compared rather easily and lead to satisfying results within study level accuracy.

Furthermore, in the context of the project work of TFTEI, the tool has been tested and applied by industry users, who possessed both the necessary input data and the actual costs of real world installations. Unfortunately, no user provided a full set of data that allows for a direct quantitative comparison, yet they confirmed the quality of the results within study level accuracy.

The validation of the second part of the work is comparably difficult, as the methodology of the model has been developed from scratch and the results focus on specific case studies and scenarios. Nevertheless, the results support the intuitive expectations when considering real option thinking in the framework of the investment decisions at hand. Furthermore, many parameters can be adapted to the needs, data sets and expectations of the users, so that the achievement of reasonable results is rather a question of calibration than one of validation. As there is no designated decision threshold (such as the achievement of a positive NPV in case of 'classical' investment decisions), the user can still adapt the parameters for decision-making (e.g. the expected return of an early investment) according to his situation, expectations and risk-preference.

7.2 Discussion and Critical Acclaim

The discussion in the following will be separated in two parts, according to the structure of the work at hand. As the two parts, the techno-economic part and the ROA, are rather different with regard to their scope, aims and assumptions, this separation seems reasonable. One general issue for discussion was already introduced in the validation sector above – a detailed validation of the overall modeling approach is difficult due to the lack of data. Nevertheless, the results and conclusions indicate an added value of the model(s) with regard to the understanding of industrial decision-making for environmental investments, and in particular for politically enforced investments, which do not gain revenues.

The system boundary for the calculations of both models is drawn around the emission control installation. Therefore, the technical and economic effects of the installation on the plant itself and vice versa is not investigated. The techno-economic model allows several adaptations (e.g. consideration of part load operation) in order to represent the plant operation correctly. Nevertheless, direct interdependencies cannot be considered and the impact of the emission control installation on the overall profitability of the plant is not investigated as part of this work. As mentioned in the introduction, this is considered acceptable, due to the lower monetary impact of air pollutants compared to climate pollutants such as CO_2, which are already strictly regulated and priced. Nevertheless, there may be an impact, particularly for older plants if new installations become necessary. This aspect has to be assessed beyond the results of this work.

7.2.1 Discussion of the Techno-economic Model

Regarding the techno-economic model, there is one overarching issue for criticism. This is the technical uniqueness of every large industrial facility. In general, no plant exactly resembles another one and these deviations massively influence the costs of an installation, the technical feasibility and, hence, the investment decision. These aspects cannot be integrated in detail in a general model as the one at hand. Therefore, even if the model achieves study level accuracy in a broader perspective, this does not mean that the results can be taken for granted for every individual plant. Particularly, but not only in case of retrofits for existing plants, certain circumstances may lead to significantly higher costs. If such issues are known in advance, the results of the model should be questioned carefully and in any case, the results of the model can never replace a detailed technical feasibility and cost study with on-site assessments.

A further weakness of the model with regard to non-industry users such as policy-makers is that there is no possibility to calculate the NO_X emissions by mass balancing or the like. This is caused by the complex formation mechanisms of NO_X. Therefore, the stack emissions before the implementation of a control technology have to be known or estimated. However, due to the detailed reporting requirements at least in industrialized regions such as the EU, there is quite a lot of information available, including the total annual NO_X emissions of individual plants, which allows for approximate estimations of emission levels if no plant-specific data is available.

A third issue is the use of the specific investment value as a direct input parameter. The quality of this value and hence the quality of the results depends primarily on the comparability of the reference plant and the investigated plant. If the plants differ in size, complexity or other technical aspects, this is not automatically taken into account. Therefore, the specific investment has to be adapted in such cases. In the case studies of chapter 6, this has been done by adapting the catalyst volume according to the amount of emissions to be abated. Based on the adaptation of the catalyst volume and considering an economies of scale factor, the specific investment value has been adapted. This is one option to deal with such an issue, the validity of the results, however, can be expected to decrease with an increasing level of deviation between the reference plant and the calculated plant.

This issue applies equally to other direct factors such as the specific catalyst volume, which is not automatically adapted if the amount of NO_X to be abated changes. Therefore, for this specific example, the methodology of the US EPA is introduced as well and used in the case studies. This methodology can be used to adapt the value of the specific catalyst volume if necessary or to benchmark the existing set of reference data.

7.2.2 Discussion of the ROA Model

This section does not aim at discussing the general advantages and drawbacks of real option theory, as this is executed in detail in literature (cf. e.g. Kruschwitz 2014). Furthermore, the model at hand is not one of the 'classical' ROA models, as it does not deal with a tradable asset, nor does it aim at setting up a risk-free portfolio. Instead, it can be denoted as a quantitative implementation of real option thinking. The NPV of an immediate investment is compared to the simulated NPV of a later investment, considering the cost of early investment (option price) and an expected return that accounts for the uncertainty with regard to the future development. It is hence an application-oriented example that displays how the ideas of ROA can be implemented in a transparent and practically applicable way, which might not perfectly suit financial theory, but is capable to answer the questions at hand.

One issue for discussion is that no differentiation has been made between the risk-free interest rate and the actual cost of capital. This issue was not considered in order to facilitate the model and its practical applicability. Furthermore, it is usually difficult to provide precise and accurate data for such a differentiation. However, this issue could easily be integrated into the model, if the corresponding data is available.

Another major aspect of discussion is the negligence of construction times. It is assumed that at the time of investment, the cash flows switch instantaneously from no abatement to full abatement. In reality, however, the planning and construction of particularly secondary installations may take several years. Nevertheless, the construction time may vary a lot and is therefore difficult to predict. If detailed information is available, this could also be integrated into the model by adapting the cash-flow matrix. Considerable construction times would lead to an actual shortening of the decision-making period. As assessed in the sensitivity analysis, however, the decision-making period has, at least for the basic scenarios, a comparably low influence on the actual ROV and return, as long as there is still room to delay the investment at all.

Furthermore, the calculation of the option price and the expected return cannot be referenced to preceding scientific studies, as this is the first study (to the best of the author's knowledge) that deals with the example of economically non-beneficial investments. Therefore, the suitability of these parameters cannot be assessed without further studies based on real-world examples. However, as mentioned already, the calculation of these parameters can be adapted at any time without questioning the general usability of the model.

Moreover, in practical applications, the derivation and particularly the prediction of future developments of prices, especially in the framework of stochastic processes is difficult. This issue may be one of the major drawbacks of the applicability of the model. Even though Bashiri and Lawryshyn (2017) published an example for how to derive the parameters of stochastic processes from past data and economic forecasts, this issue remains crucial for the accuracy and reliability of the results. As this is a different scientific field, however, it goes beyond the scope of this work to assess it in detail. Furthermore, the ROA developed in this study is comparably flexible with regard to the selected stochastic process due to its numeric approach. Therefore, all sorts of processes can be implemented, as long as the future prices can be derived by the random walk approach for a large number of paths, which then serve as input for the Monte-Carlo-Simulation.

Another issue for criticism may be the temporal resolution, which is comparably low in the given examples, with a period length of one year. However, for the question at hand, this appears sufficient. Nevertheless, a larger amount of time-steps (e.g. half-years, quarters or months) could be integrated easily and would be feasible with regard to the computational effort of the model.

In this study, the operating costs were not simulated but defined deterministically. In many applications, however, the operating costs, particularly with regard to consumable prices are a major source of uncertainty. Yet, as discussed above, it is very difficult to simulate the behavior of prices according to a predefined stochastic process. Therefore, for the application at hand, two deterministic scenarios were considered in order to assess the impact of operating costs. If the operating costs shall be simulated, this could be modeled like the NO_X market scenario, with a drift rate and volatility for the operating costs that can either correlate with the investment development or a different set of random numbers can be assumed in order to avoid correlation, which is probably the more likely case.

Furthermore, there was no higher inflation rate assumed for India than for the EU. This issue was already discussed in the context of the case studies. Even though not very realistic, this assumption was made in order to allow for a comparison that is free of inflation impacts. In the sensitivity analysis, a higher inflation rate was assessed and in a real example, the actual inflation rate can be chosen according to the local circumstances. The aim of this work is not to derive quantitative policy conclusions for individual countries and therefore, this simplification/falsification is considered acceptable for the sake of transparency and methodological understanding.

A further issue with regard to policy implications that has already been mentioned is the profitability of the plant itself that should not be endangered, nor should the policy measure be compensated by rebound or leakage effects. Such effects need to be considered by policy-makers, yet they have to be assessed separately as this would go beyond the scope of this work.

As the focus of this research is on industrial decision-making at an individual plant scale, decision-makers with differing risk perceptions and decision-making criteria are to be expected. Therefore, in contrast to macroeconomic considerations with average or common practice evaluation, there is no common strategy of decision-makers to be assumed. The assessment of rather similar investments may differ a lot among different investors. The resulting decisions depend not only on external influencing factors such as prices, policies and other types of risks; but also on the (company) culture, previous experiences, specific knowledge and personal or institutional incentives of the decision-maker or the decision-making board. An assessment of personal incentive structures of managers is provided in Friedl (2007). Yet, investigating the detailed impact thereof on investment decisions is not in the scope of this work but regarded as an area of future research.

Two further aspects that can be regarded as weaknesses of the ROA at hand, but also as areas of future work are the consideration of further options beyond the deferral option and the valuation of the marketing aspect of environmental friendliness. Both aspects will be mentioned in more detail in the outlook section. They are not considered in this study in order to limit the complexity of the overall model. This, however, does not mean that these aspects are not of relevance in the context of environmental investments.

7.3 Transferability

The transferability of the models in this study differs for the two parts. While the techno-economic model is specifically tailored to NO_X abatement installations, the ROA is more broadly applicable. Nevertheless, the key components of the techno-economic model can also be transferred to other applications. The general structure of investment (CAPEX), variable and fixed operating costs (OPEX) can be applied for most industrial applications. The individual cost items and the underlying reference values, however, have to be updated for other applications. Therefore, the general approach is transferable, the model, however, cannot directly be used for other types of installations. For NO_X abatement installations in other sectors, however, it may be possible to adapt only a few differing values with regard to the deviations of the considered sector. Examples of this kind are waste incineration plants or cement production plants. In such plants, the same techniques are used (SCR and SNCR) but some operating parameters, such as the dust load of the flue gas, differ. Hence, the impacts of these differing parameters need to be assessed before using the model. If these impacts are understood and considered correctly, it is supposed to be possible to use the model accordingly.

The ROA model is more broadly applicable. Generally, it can be used for all politically enforced investments that do not gain economic profit. The cost structure of investments, operating costs and other costs such as emission fees over the lifetime needs to be known and the problem to be investigated has to be comparable to the problem at hand. Furthermore, the prerequisites of a real option model have to be fulfilled, i.e. there must be flexibility with regard to the investment timing and uncertainty regarding the future development of at least one important parameter. Typical examples that can be expected to fulfill these criteria are abatement installations for other air pollutants, but also for wastewater cleaning or industrial waste disposal.

7.4 Summary and Outlook

After introducing the most relevant technical aspects of NO_X abatement in large combustion plants and the scientific basis for environmental investment appraisal, the work at hand investigates three major research questions:

- How can the CAPEX and OPEX for NO_X abatement installations in LCP be estimated precisely and efficiently in the early stages of investment planning or by company external entities?
- How can the optimal timing of the investment be assessed based on the ROA approach?
- Which policy instruments influence investment decisions in the considered framework in which way?

In order to answer these questions, a single-plant oriented approach is selected, which investigates all research questions on an individual plant scale that allows for considering technical specifics in detail. Thereof, general conclusions and implications for policy can be derived, which may, however, not be applicable for all sorts of plants. For a detailed national or regional inventory or integrated assessment model of the considered industry sector, a more comprehensive approach is necessary. Yet, such large-scale assessments may blur the specifics of individual plants, which are of particular relevance for investors, but also for policy-makers in smaller countries with few installations, or if e.g. leakage effects from specific plants shall be avoided.

The first research question is targeted in chapter 4 with the development of a calculation methodology focusing on the SCR and SNCR technology that considers and assesses investments, fixed and variable operating costs.

The second part, the investigation of the optimal timing of an investment, focusses on environmental investments that do not gain profits, i.e. they are directly enforced by policy. The specifics of such investment decisions lead to several peculiarities: the investment decision needs to take place in a predefined timeframe, the decision-making period, which is set by the adaptation time for industry that is usually specified in newly enforced regulation.

Furthermore, the investment is mandatory, i.e. it has to be executed by the end of the decision-making period at the latest. Consequently, there is no predefined threshold value for decision-making, such as a certain NPV that triggers the investment. Instead, a rolling horizon approach is to be used that compares an immediate investment with a delayed investment. The standard decision is to delay the investment as much as legally feasible, therefore, the option is to advance the investment compared to the latest possible period. The real option value of an early investment increases, if a later investment leads to increasing expenditures. This may be the case if investment expenditures increase significantly, or if additional policy measures interact with the economic decision.

In order to assess this option to invest earlier than necessary, a two-perspective ROA model has been developed. The two perspectives are the savings and the losses perspective with the savings perspective being more future-oriented and the losses perspective rather present-oriented. This orientation is caused by the calculation of the option price, which directly influences the option value calculated numerically via a Monte-Carlo-Simulation.

The influence of policy measures on investment decisions in the considered framework is assessed via exemplary case studies and scenarios. For a plant in the EU and one in India, SCR and SNCR installations are assessed via the techno-economic model and the ROA model. A very general conclusion of the results is that the real option value increases with increasing uncertainty. Therefore, political ambiguity, as well as economic uncertainty, directly influences investment decisions. The threshold to advance an investment in the considered framework is generally comparably high; therefore, disruptive settings are necessary in order to promote early investments. Furthermore, the implementation of directly emission related costs such as emission fees, taxes or emission-trading schemes has a stronger impact with regard to early investments than positive instruments such as public support schemes have.

The model and results presented in this work open up a broad field of subjects for future work. With regard to the success of policy measures, the impact of rebound effects shall be mentioned at this stage, as this aspect is often underestimated with regard to its environmental impact. Rebound effects themselves, as well as their interference with real option thinking, are considered a promising branch for future research in order to better explain the outcome of policy instruments and thus to improve their design and implementation.

Furthermore, a detailed understanding of ROA and real option thinking from a behavioral economics perspective is necessary to evaluate and validate the results of this research. An important aspect in this context is not only the question, whether the implications of ROA and real option thinking are correct, but also to which extent decision-makers already think in options or which effects could be achieved if they were trained to do so. Based on the results of a behavioral economics study, an agent-based model could deliver quantitative results regarding the implications of real option thinking and the use of ROA as investment decision-making method for environmental investments. Andalib et al. (2018) recently published an exemplary work in this field with a focus on project management and a lot more research in this direction can be expected in the coming years. Mathematical models to incorporate risk aversion in real option analyses have been published for example by Hugonnier and Morellec (2003) and Ewald and Yang (2008). These models are, however, very complex from a mathematical point of view and difficult to implement for many real-world applications. Therefore, further studies in this direction with regard to practical implementation would be helpful and might lead to actual progress. Such studies could also provide more information on the optimal determination of parameters such as the option price and the expected return in the considered framework.

In the same context, the personal incentive structures for managers and the thereof resulting decisions with regard to environmental investments are another area of ongoing and future work. There are already several scientific and practice-oriented publications on related issues (cf. e.g. Flyvbjerg and Sunstein 2015; van der Slot et al. 2015; Vose 2015), based on early works in the field, such as Hirschman (1967) and Pratt and Zeckhauser (1985). Yet, a specific study focusing on ROA and real option thinking would support the understanding of drivers and drawbacks in this specific field.

Moreover, a task for future research is to investigate alternative investment options (e.g. growth options, staging options, switching options) in more detail in the considered context and implement them as enhancement of the ROA model. To mention one example for a staging option, many emission abatement installations can consist of one big reactor or of two simultaneously operated smaller reactors. By choosing the two-reactor solution, only one reactor with all the pipework, etc. prepared for a second one can be installed in a first step. If sometime later a lower emission threshold needs to be met, the second reactor can be retrofitted rather easily.

Directly related to the work at hand is the task of defining the option price. Future research with regard to its precise definition is recommended as there is no scientific reference available that identifies a suitable value or calculation formula.

Another issue that has not been considered in this study due to lacking data and knowledge is the value of the good reputation that comes with installing emission abatement measures. The marketing of environmental friendliness is certainly a considerable aspect nowadays. Its monetary value, however, is very difficult to evaluate and can be expected to vary significantly in different regions and societies.

Finally, the assessment of the economic efficiency of policy measures is another issue that is not targeted by this work. In order to investigate the value of the abated emissions in relation to the costs of policy incentives, a more macroeconomically oriented study is necessary. Yet not only the economic efficiency of the policy measure itself needs to be investigated, but also its impact on the targeted industry in order to assess e.g. leakage effects, as discussed already.

To conclude, this work delivers a methodology to assess NO_X emission control measures in LCP from a techno-economic perspective and supports decision-making for such installations via a ROA. Even though the focus of the work is on the development of a suitable methodology for individual plants, a derivation of policy conclusions for the investigated examples is possible. Yet, in order to quantitatively assess results and effects at a broader scale such as a national economy sector, further macroeconomic and behavioral economics studies appear reasonable, in order to improve the understanding of industrial decision-making with the aim of actively promoting early and comprehensive environmental investments.

Annex

A. Summary of International Nitrogen Oxide Emission Regulation

Country Name	Country Code	Emission Limits	Immission Limits	Emission Limit Value (ELV) [mg/Nm³] for a new installation		References
				100 MW gas turbine	1000 MW coal-fired boiler	
Australia	AUS	x	x	N/A (state specific)	N/A (state specific)	[1]
Azerbaijan	AZE		x	tbd	tbd	[2]
Brazil	BRA	x		50	-	[3]
Canada	CAN	x		depending on the power and heat output of the plant	depending on the power and heat output of the plant	[4]
Chile	CHL	x		50	200	[5]
China	CHN	x		50	100	[6]
Dominica	DMA	x		N/A	250	[7]
EU-28*	EU	x		15-35	50-85	[8]
India	IND	x		-	100	[9]
Indonesia	IDN	x		320	750	[10],[11]
Japan	JPN	x		70 ppm (ca. 144 mg/Nm³)	200 ppm (ca. 410 mg/Nm³)	[12]
Malaysia	MYS	x		150	500	[13]
Mexico	MEX	x		N/A	225-769 (depending on the region)	[14]
Norway	NOR		x	tbd	tbd	[15]

Pakistan	PAK	x		400	300 ng/J$_{heat\ input}$ (cannot be transferred in mg/Nm³ without additional information)	[16]
Philippines	PHL	x		500	1000	[17]
Rep. of Korea	KOR	x		N/A	164	[18]
Russia	RUS		x	tbd	tbd	[19],[20]
Serbia	SCG	x		50	200	[21],[22]
Singapore	SGP	x		700	700	[23]
South Africa	ZAF	x		50	750	[24]
Switzerland	CHE	x		20	150	[25]
Taiwan	TWN	x		246	513	[26]
Thailand	THA	x		120 ppm (ca. 246 mg/Nm³)	200 ppm (ca. 410 mg/Nm³)	[27]
Trinidad and Tobago	TTO	x		500	500	[28]
Turkey	TUR	x		50	200	[29],[30]
Ukraine	UKR	x		N/A	500	[31]
United States	USA	x		N/A (state specific and in US units that cannot be converted directly)	N/A (state specific and in US units that cannot be converted directly)	[32]
Vietnam	VNM	x		390-910 (location dependent)	330-1200 (location dependent)	[33],[34]

Explanation:

- \- No ELV in force (national air quality standards, however, apply accordingly)
- tbd ELV need to be defined for every plant individually in order to meet the regional air quality standards
- N/A ELV seem to be existing but are not available/accessible (e.g. due to translation difficulties)

References:

[1] https://www.iea-coal.org/wp-content/uploads/2017/12/Australia-emission-standards.pdf

[2] http://www.unece.org/fileadmin/DAM/env/epr/epr_studies/azerbaijan%20II.pdf

[3] http://www.mma.gov.br/port/conama/legiabre.cfm?codlegi=660
[4] https://www.iea-coal.org/wp-content/uploads/2017/12/Canada-emission-standard.pdf
[5] http://centralenergia.cl/uploads/2011/06/Norma_emision_centrales_ termoe-lectricas_Decreto_13.pdf
[6] http://www.neec.no/wp-content/uploads/ChinaFAQs.pdf
[7] https://www.iea-coal.org/wp-content/uploads/2017/12/Dominica.pdf
[8] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017D1442&from=EN
[9] https://www.iea-coal.org/wp-content/uploads/2017/12/new-India-standard.pdf
[10] https://www.iea-coal.org/wp-content/uploads/2017/12/Indonesia-emission-standards.pdf
[11] http://hukum.unsrat.ac.id/lh/menlh2008_21_1.pdf
[12] https://www.env.go.jp/en/air/aq/air/air4_table.html
[13] http://www.federalgazette.agc.gov.my/outputp/pua_20140604_P.U.%20%28A%29%20151-peraturan-peraturan%20kualiti%20alam%20 sekeliling%20%28udara%20bersih%29%202014.pdf
[14] http://siga.jalisco.gob.mx/Assets/documentos/normatividad/nom085 semarnat1994.htm
[15] http://miljodirektoratet.no/en/Legislation1/Regulations/Pollution-Regulations/Chapter-7/
[16] http://serl.pk/lawfile/24/NEQs-industrial-gases.pdf
[17] http://policy.denr.gov.ph/2000/ENV_DAO_2000-81.pdf
[18] https://www.iea-coal.org/wp-content/uploads/2017/12/South-Korea.pdf
[19] http://www.oecd.org/env/outreach/38118149.pdf
[20] http://uk.practicallaw.com/6-503-2842#a249373
[21] https://serbia-energy.eu/serbia-eps-will-shut-8-coal-fired-units-2024/
[22] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32001L0080&from=EN
[23] https://www.iea-coal.org/wp-content/uploads/2017/12/Singapore.pdf
[24] http://www.saaqis.org.za/filedownload.aspx?fileid=885
[25] https://www.admin.ch/opc/de/classified-compilation/19850321/index.html#app2
[26] https://www.iea-coal.org/wp-content/uploads/2017/12/Taiwan-emission-standards.pdf

[27] https://bit.ly/2K2Gpfe
[28] https://www.iea-coal.org/wp-content/uploads/2017/12/Trinidad-and-Tobago.pdf
[29] http://www.tepav.org.tr/upload/files/haber/1427475571-5.Turkey___s_Compliance_with_the_Industrial_Emissions_Directive.pdf
[30] https://www.iea-coal.org/wp-content/uploads/2017/12/Turkey-emissions-standard.pdf
[31] https://www.iea-coal.org/wp-content/uploads/2017/12/Ukraine-1.pdf
[32] https://www.gpo.gov/fdsys/pkg/CFR-2011-title40-vol6/xml/CFR-2011-title40-vol6-part60.xml
[33] https://www.iea-coal.org/wp-content/uploads/2017/12/Vietnam-emission-standard.pdf
[34] https://www.env.go.jp/air/tech/ine/asia/vietnam/files/law/QCVN%2022-2009.pdf

Data and links as of 14 November 2018.

* More stringent national regulation may apply in some EU countries.

B. Further Calculation Results of the ROA in Section 6.4

Overview of all results, ROV in M€:

σ	μ	NO_X fee [€/t]	EU SCR base	EU SCR tight	EU SNCR	IND SCR	IND SNCR
Increasing investment							
0.01	0.04		0	0	0	0	0
0.05	0.04		0.094	0.102	0.035	0.037	0
0.01	0.08		0.590	0.639	0.215	0.149	0
0.05	0.08		0.914	1.027	0.376	0.546	0.026
0.01	0.12		2.705	3.078	1.159	1.974	0.073
0.05	0.12		2.750	3.133	1.184	2.071	0.304
0.01	0.16		4.936	5.658	2.164	4.078	0.955
0.05	0.16		4.940	5.663	2.167	4.092	1.039
Increasing investment with high consumable costs							
0.01	0.04		0	0	0	0	0
0.05	0.04		0.064	0.066	0.020	0.009	0
0.01	0.08		0.368	0.355	0.089	0.002	0
0.05	0.08		0.755	0.819	0.278	0.247	0
0.01	0.12		2.435	2.717	0.979	1.146	0
0.05	0.12		2.501	2.802	1.021	1.395	0.017
0.01	0.16		4.666	5.296	1.984	3.247	0.005
0.05	0.16		4.674	5.307	1.990	3.293	0.213
Increasing investment with NO_X fees							
0.05	0	500	0.011	0.010	0.022	0.189	0.002
0.05	0.02	500	0.073	0.069	0.102	0.577	0.016
0.05	0.04	500	0.299	0.300	0.302	1.248	0.079
0.05	0	1000	0.060	0.049	0.276	2.442	1.534
0.05	0.02	1000	0.261	0.233	0.590	3.344	1.970
0.05	0.04	1000	0.739	0.714	0.997	4.282	2.420

0.05	0	2000	0.674	0.538	1.831	8.698	7.285
0.05	0.02	2000	1.399	1.260	2.270	9.622	7.727
0.05	0.04	2000	2.315	2.257	2.720	10.564	8.177
0.05	0	4000	4.142	3.969	5.286	21.255	18.798
0.05	0.02	4000	5.117	5.087	5.727	22.179	19.239
0.05	0.04	4000	6.116	6.238	6.177	23.122	19.689
0.05	0	8000	11.758	11.981	12.199	46.370	41.822
0.05	0.02	8000	12.737	13.111	12.640	47.294	42.263
0.05	0.04	8000	13.737	14.263	13.090	48.236	42.714
σ_NO_X	μ_NO_X	NO_X fee [€/t]	EU SCR base	EU SCR tight	EU SNCR	IND SCR	IND SNCR
NO_X market*							
0.05	0.05	500	0	0	0.042	0.006	1.228
0.1	0.05	500	0	0	0.139	0.540	1.241
0.05	0.1	500	0.018	0	1.813	1.060	5.371
0.1	0.1	500	0.061	0	1.824	1.081	5.373
0.05	0.05	1000	0.001	0	1.247	3.213	5.290
0.1	0.05	1000	0.034	0	1.258	3.213	5.291
0.05	0.1	1000	1.182	0.013	5.251	5.976	13.577
0.1	0.1	1000	1.287	0.118	5.253	5.977	13.580
0.05	0.05	2000	1.554	0.563	4.120	10.281	13.415
0.1	0.05	2000	1.554	0.569	4.121	10.282	13.416
0.05	0.1	2000	5.827	2.702	12.128	15.806	29.989
0.1	0.1	2000	5.828	2.702	12.131	15.808	29.995
0.05	0.05	4000	6.585	5.186	9.865	24.418	29.664
0.1	0.05	4000	6.586	5.186	9.867	24.419	29.668
0.05	0.1	4000	15.131	9.464	25.882	35.467	62.812
0.1	0.1	4000	15.134	9.465	25.888	35.471	62.824
p	h	NO_X fee [€/t]	EU SCR base	EU SCR tight	EU SNCR	IND SCR	IND SNCR
Discontinued Subsidies (σ= 0.05, μ=0.015)**							
p1	10%		0.078	0.084	0.029	0.029	0

p1	20%		0.379	0.419	0.150	0.187	0.004
p1	30%		1.047	1.174	0.433	0.642	0.033
p2	10%		0.210	0.228	0.079	0.081	0.001
p2	20%		1.317	1.457	0.052	0.662	0.015
p2	30%		3.934	4.413	1.629	2.434	0.127
p3	10%		0.125	0.136	0.047	0.048	0
p3	20%		0.698	0.771	0.276	0.348	0.008
p3	30%		2.019	2.264	0.835	1.243	0.064
Discontinued Subsidies with NO_X fees (σ= 0.05, μ=0.015)							
p1	10%	500	0.266	0.265	0.280	0.019	0.914
p1	20%	500	0.855	0.897	0.664	0.139	1.427
p1	30%	500	1.785	1.935	1.146	0.525	1.946
p2	10%	500	0.688	0.690	0.695	0.054	2.023
p2	20%	500	2.887	3.040	2.155	0.496	4.046
p2	30%	500	6.546	7.123	4.061	1.997	6.116
p3	10%	500	0.415	0.415	0.425	0.032	1.296
p3	20%	500	1.549	1.628	1.172	0.260	2.313
p3	30%	500	3.389	3.682	2.129	1.018	3.348
p1	10%	1000	0.688	0.659	0.972	4.246	3.797
p1	20%	1000	1.573	1.612	1.488	5.376	4.344
p1	30%	1000	2.655	2.833	2.008	6.503	4.891
p2	10%	1000	1.698	1.643	2.126	7.538	5.433
p2	20%	1000	5.071	5.257	4.165	12.046	7.616
p2	30%	1000	9.355	10.085	6.240	16.543	9.799
p3	10%	1000	1.043	1.005	1.369	5.347	4.341
p3	20%	1000	2.766	2.855	2.392	7.599	5.431
p3	30%	1000	4.914	5.278	3.429	9.846	6.522

* in the NO_X market scenario, the NO_X fee displays the initial price of NO_X emissions that serves as basis for the stochastic simulation of future prices.

** The probability settings p for the discontinued subsidies scenario are:
p1: p_0=0 %, p_1=25 %, p_2=25 %, p_3=25 %, p_4=25 %,
p2: p_0=0 %, p_1=100 %, p_2=0 %, p_3=0 %, p_4=0 %,
p3: p_0=0 %, p_1=50 %, p_2=25 %, p_3=15 %, p_4=10 %.

Overview of all results, R in %:

σ	μ	NO_X fee [€/t]	EU SCR base	EU SCR tight	EU SNCR	IND SCR	IND SNCR
Increasing investment							
0.01	0.04		0.00%	0.00%	0.00%	0.00%	0.00%
0.05	0.04		0.19%	0.18%	0.16%	0.08%	0.00%
0.01	0.08		1.18%	1.11%	0.96%	0.32%	0.00%
0.05	0.08		1.83%	1.78%	1.67%	1.16%	0.12%
0.01	0.12		5.42%	5.33%	5.15%	4.19%	0.32%
0.05	0.12		5.51%	5.43%	5.26%	4.40%	1.35%
0.01	0.16		9.88%	9.80%	9.62%	8.66%	4.24%
0.05	0.16		9.89%	9.81%	9.63%	8.69%	4.62%
Increasing investment with high consumable costs							
0.01	0.04		0.00%	0.00%	0.00%	0.00%	0.00%
0.05	0.04		0.13%	0.11%	0.09%	0.02%	0.00%
0.01	0.08		0.74%	0.61%	0.40%	0.00%	0.00%
0.05	0.08		1.51%	1.42%	1.24%	0.52%	0.00%
0.01	0.12		4.87%	4.70%	4.35%	2.43%	0.00%
0.05	0.12		5.01%	4.85%	4.54%	2.96%	0.08%
0.01	0.16		9.34%	9.17%	8.82%	6.89%	0.02%
0.05	0.16		9.36%	9.19%	8.84%	6.99%	0.95%
Increasing investment with NO_X fees							
0.05	0	500	0.02%	0.02%	0.10%	0.40%	0.01%
0.05	0.02	500	0.15%	0.12%	0.45%	1.23%	0.07%
0.05	0.04	500	0.60%	0.52%	1.34%	2.65%	0.35%
0.05	0	1000	0.12%	0.08%	1.23%	5.18%	6.82%
0.05	0.02	1000	0.52%	0.40%	2.62%	7.10%	8.76%
0.05	0.04	1000	1.48%	1.24%	4.43%	9.09%	10.76%
0.05	0	2000	1.35%	0.93%	8.14%	18.47%	32.38%
0.05	0.02	2000	2.80%	2.18%	10.09%	20.43%	34.34%
0.05	0.04	2000	4.63%	3.91%	12.09%	22.43%	36.34%
0.05	0	4000	8.29%	6.87%	23.49%	45.13%	83.55%

0.05	0.02	4000	10.24%	8.81%	25.45%	47.09%	85.51%
0.05	0.04	4000	12.24%	10.80%	27.45%	49.09%	87.51%
0.05	0	8000	23.54%	20.75%	54.22%	98.45%	185.88%
0.05	0.02	8000	25.50%	22.70%	56.18%	100.41%	187.84%
0.05	0.04	8000	27.50%	24.70%	58.18%	102.41%	189.84%
σ_NO$_X$	μ_NO$_X$	NO$_X$ fee [€/t]	EU SCR base	EU SCR tight	EU SNCR	IND SCR	IND SNCR
NO$_X$ market*							
0.05	0.05	500	0.00%	0.00%	0.18%	0.01%	5.46%
0.1	0.05	500	0.00%	0.00%	0.62%	1.15%	5.52%
0.05	0.1	500	0.04%	0.00%	8.06%	2.25%	23.87%
0.1	0.1	500	0.12%	0.00%	8.11%	2.30%	23.88%
0.05	0.05	1000	0.00%	0.00%	5.54%	6.82%	23.51%
0.1	0.05	1000	0.07%	0.00%	5.59%	6.82%	23.52%
0.05	0.1	1000	2.37%	0.02%	23.34%	12.69%	60.34%
0.1	0.1	1000	2.58%	0.20%	23.35%	12.69%	60.36%
0.05	0.05	2000	3.11%	0.97%	18.31%	21.83%	59.62%
0.1	0.05	2000	3.11%	0.99%	18.32%	21.83%	59.63%
0.05	0.1	2000	11.67%	4.68%	53.90%	33.56%	133.28%
0.1	0.1	2000	11.67%	4.68%	53.92%	33.56%	133.31%
0.05	0.05	4000	13.18%	8.98%	43.84%	51.84%	131.84%
0.1	0.05	4000	13.19%	8.98%	43.85%	51.85%	131.86%
0.05	0.1	4000	30.29%	16.39%	115.03%	75.30%	279.16%
0.1	0.1	4000	30.30%	16.39%	115.06%	75.31%	279.22%
p	h	NO$_X$ fee [€/t]	EU SCR base	EU SCR tight	EU SNCR	IND SCR	IND SNCR
Discontinued Subsidies (σ= 0.05, μ=0.015)**							
p1	10%		0.16%	0.15%	0.13%	0.06%	0.00%
p1	20%		0.76%	0.73%	0.67%	0.40%	0.02%
p1	30%		2.10%	2.03%	1.92%	1.36%	0.15%
p2	10%		0.42%	0.39%	0.35%	0.17%	0.00%
p2	20%		2.64%	2.52%	0.23%	1.41%	0.07%

p2	30%		7.88%	7.64%	7.24%	5.17%	0.56%
p3	10%		0.25%	0.24%	0.21%	0.10%	0.00%
p3	20%		1.40%	1.34%	1.23%	0.74%	0.04%
p3	30%		4.04%	3.92%	3.71%	2.64%	0.28%
Discontinued Subsidies with NO_X fees (σ= 0.05, μ=0.015)							
p1	10%	500	0.53%	0.46%	1.24%	0.04%	4.06%
p1	20%	500	1.71%	1.55%	2.95%	0.30%	6.34%
p1	30%	500	3.57%	3.35%	5.09%	1.11%	8.65%
p2	10%	500	1.38%	1.19%	3.09%	0.11%	8.99%
p2	20%	500	5.78%	5.26%	9.58%	1.05%	17.98%
p2	30%	500	13.11%	12.33%	18.05%	4.24%	27.18%
p3	10%	500	0.83%	0.72%	1.89%	0.07%	5.76%
p3	20%	500	3.10%	2.82%	5.21%	0.55%	10.28%
p3	30%	500	6.78%	6.38%	9.46%	2.16%	14.88%
p1	10%	1000	1.38%	1.14%	4.32%	9.01%	16.88%
p1	20%	1000	3.15%	2.79%	6.61%	11.41%	19.31%
p1	30%	1000	5.32%	4.91%	8.92%	13.81%	21.74%
p2	10%	1000	3.40%	2.85%	9.45%	16.00%	24.15%
p2	20%	1000	10.15%	9.10%	18.51%	25.58%	33.85%
p2	30%	1000	18.73%	17.46%	27.73%	35.12%	43.55%
p3	10%	1000	2.09%	1.74%	6.08%	11.35%	19.29%
p3	20%	1000	5.54%	4.94%	10.63%	16.13%	24.14%
p3	30%	1000	9.84%	9.14%	15.24%	20.90%	28.99%

* in the NO_X market scenario, the NO_X fee displays the initial price of NO_X emissions that serves as basis for the stochastic simulation of future prices.

** The probability settings p for the discontinued subsidies scenario are:
p1: p_0=0 %, p_1=25 %, p_2=25 %, p_3=25 %, p_4=25 %,
p2: p_0=0 %, p_1=100 %, p_2=0 %, p_3=0 %, p_4=0 %,
p3: p_0=0 %, p_1=50 %, p_2=25 %, p_3=15 %, p_4=10 %.

Overview of all results, number of paths that recommend an immediate investment:

σ	μ	NO_X fee [€/t]	EU SCR base	EU SCR tight	EU SNCR	IND SCR	IND SNCR
Increasing investment							
0.01	0.04		0	0	0	0	0
0.05	0.04		6 184	5 888	5 271	2 723	54
0.01	0.08		84 427	82 300	77 060	38 258	0
0.05	0.08		s40 941	40 016	38 115	28 632	3 808
0.01	0.12		100 000	100 000	100 000	99 999	39 499
0.05	0.12		80 447	79 916	78 692	71 796	31 441
0.01	0.16		100 000	100 000	100 000	100 000	99 997
0.05	0.16		96 078	95 929	95 575	93 472	72 439
Increasing investment with high consumable costs							
0.01	0.04		0	0	0	0	0
0.05	0.04		4 365	3 891	3 049	720	0
0.01	0.08		67 437	60 464	45 122	710	0
0.05	0.08		35 232	33 548	30 100	14 712	35
0.01	0.12		100 000	100 000	100 000	98 695	0
0.05	0.12		76 783	75 610	73 008	56 296	2 485
0.01	0.16		100 000	100 000	100 000	100 000	4430
0.05	0.16		95 027	94 701	93 865	87 467	23 307
Increasing investment with NO_X fees							
0.05	0	500	919	711	3 664	12 893	372
0.05	0.02	500	5 085	4 245	13 865	31 953	2 547
0.05	0.04	500	17 142	15 181	33 441	55 479	10 771
0.05	0	1000	4 418	3 188	32 933	83 347	91 729
0.05	0.02	1000	15 683	12 611	56 320	92 208	96 459
0.05	0.04	1000	36 105	31 461	75 679	96 698	98 647
0.05	0	2000	35 473	26 589	95 562	100 000	100 000
0.05	0.02	2000	58 892	49 634	98 249	100 000	100 000

0.05	0.04	2000	77 379	70 910	99 395	100 000	100 000
0.05	0	4000	95 903	92 023	100 000	100 000	100 000
0.05	0.02	4000	98 386	96 581	100 000	100 000	100 000
0.05	0.04	4000	99 452	98 700	100 000	100 000	100 000
0.05	0	8000	100 000	100 000	100 000	100 000	100 000
0.05	0.02	8000	100 000	100 000	100 000	100 000	100 000
0.05	0.04	8000	100 000	100 000	100 000	100 000	100 000
σ_NO_X	μ_NO_X	NO_X fee [€/t]	EU SCR base	EU SCR tight	EU SNCR	IND SCR	IND SNCR
NO_X market*							
0.05	0.05	500	0	0	21 117	5 214	99 867
0.1	0.05	500	15	0	27 196	15 246	89 233
0.05	0.1	500	786	0	99 982	99 773	100 000
0.1	0.1	500	8 341	83	94 954	88 769	99 968
0.05	0.05	1000	365	0	99 948	100000	100000
0.1	0.05	1000	6 262	77	91 928	100 000	100 000
0.05	0.1	1000	96 287	5 456	100 000	100 000	100 000
0.1	0.1	1000	76 080	16 488	99 976	100 000	100 000
0.05	0.05	2000	100 000	99 346	100 000	100 000	100 000
0.1	0.05	2000	96 351	82 051	99 992	100 000	100 000
0.05	0.1	2000	100 000	100 000	100 000	100 000	100 000
0.1	0.1	2000	99 996	99 917	100 000	100 000	100 000
0.05	0.05	4000	100 000	100 000	100 000	100 000	100 000
0.1	0.05	4000	100 000	100 000	100 000	100 000	100 000
0.05	0.1	4000	100 000	100 000	100 000	100 000	100 000
0.1	0.1	4000	100 000	100 000	100 000	100 000	100 000
p	h	NO_X fee [€/t]	EU SCR base	EU SCR tight	EU SNCR	IND SCR	IND SNCR
Discontinued Subsidies (σ= 0.05, μ=0.015)**							
p1	10%		4 521	4 253	3 762	1 927	35
p1	20%		13 081	12 633	11 744	7 604	454
p1	30%		22 274	21 814	20 882	16 299	2 641

p2	10%		10 052	9 490	8 498	4 519	97
p2	20%		37 733	36 562	34304	23120	1595
p2	30%		70 846	69 754	67 569	54 882	9 637
p3	10%		6 517	6 151	5 517	2 913	63
p3	20%		21 826	21 155	19 782	13 051	857
p3	30%		39 200	38 526	37 196	29 761	4 986
Discontinued Subsidies with NO_X fees (σ= 0.05, μ=0.015)							
p1	10%	500	13 441	11 820	27 172	1 322	64 065
p1	20%	500	25 117	23 357	37 925	5 866	66 130
p1	30%	500	32 119	30 773	41 438	14 009	66 274
p2	10%	500	27 247	24 356	50 706	3 122	92 450
p2	20%	500	64 695	61 220	84 676	18 195	99 433
p2	30%	500	89 562	87 702	97 289	48 019	99 986
p3	10%	500	18 540	16 458	35 957	2 002	74 403
p3	20%	500	39 418	37 051	54 949	10 188	78 210
p3	30%	500	52 556	50 988	61 592	25 804	78 498
p1	10%	1000	29 567	25 385	66427	93053	99939
p1	20%	1000	39 817	36 474	68 110	93 063	99 939
p1	30%	1000	42 902	40 384	68 123	93 063	99 939
p2	10%	1000	54 226	47 946	93 871	99 963	100 000
p2	20%	1000	86 773	82 879	99 598	100 000	100 000
p2	30%	1000	97 825	96 808	99 988	100 000	100 000
p3	10%	1000	38 779	33 798	76 364	95 403	99 957
p3	20%	1000	56 961	53 374	79 481	95 423	99 957
p3	30%	1000	62 765	60 743	79 691	95 423	99 957

* in the NO_X market scenario, the NO_X fee displays the initial price of NO_X emissions that serves as basis for the stochastic simulation of future prices.

** The probability settings p for the discontinued subsidies scenario are:
p1: p_0=0 %, p_1=25 %, p_2=25 %, p_3=25 %, p_4=25 %,
p2: p_0=0 %, p_1=100 %, p_2=0 %, p_3=0 %, p_4=0 %,
p3: p_0=0 %, p_1=50 %, p_2=25 %, p_3=15 %, p_4=10 %.

Results of the EU SNCR increasing investment with NOx fees scenario (σ= 0.05, μ=0.015, cf. Figure 6-3):

NO_X fee [€/t]	Base		
	ROV	R	Invest
0	0.003	0.01%	545
250	0.018	0.08%	2 851
500	0.073	0.32%	10 474
750	0.222	0.99%	27 115
1000	0.501	2.23%	50 553
1250	0.879	3.91%	72 237
1500	1.299	5.77%	86 413
1750	1.728	7.68%	94 142
2000	2.159	9.60%	97 767
2250	2.591	11.52%	99 272
2500	3.024	13.44%	99 813
2750	3.455	15.36%	99 964
3000	3.887	17.28%	99 997
3250	4.320	19.20%	100 000
3500	4.752	21.12%	100 000

References

Abadie, Luis M.; Chamorro, José M. (2008): European CO2 prices and carbon capture investments. In *Energy Economics* 30 (6), pp. 2992–3015. DOI: 10.1016/j.eneco.2008.03.008.

Adkins, Roger; Paxson, Dean (2016): Subsidies for Renewable Energy Facilities under Uncertainty. In *The Manchester School* 84 (2), pp. 222–250. DOI: 10.1111/manc.12093.

Ahrens, Ralph H. (2017): Gerangel ums Stickoxid (VDI Nachrichten, 39). Available online at https://www.vdi-nachrichten.com/Technik/Gerangel-Stickoxid, checked on 11/9/2018.

Ammann, Manuel (2001): Credit Risk Valuation. Methods, Models, and Applications. Second edition. Berlin, Heidelberg: Springer Berlin Heidelberg (Springer Finance).

Ampofo, Kwasi Darkwa (2017): Reasons why Real Options Analysis (ROA) is not widely adopted in the mineral industry. PhD Thesis. The University of Queensland, Brisbane.

Andalib, Mohammad Saied; Tavakolan, Mehdi; Gatmiri, Behrouz (2018): Modeling managerial behavior in real options valuation for project-based environments. In *International Journal of Project Management* 36 (4), pp. 600–611. DOI: 10.1016/j.ijproman.2018.02.001.

Aulisi, Andrew (2005): Greenhouse gas emissions trading in U.S. states. Observations and lessons from the OTC NOx budget program. Washington, D.C.: World Resources Institute (WRI white paper).

Baecker, Philipp; Hommel, Ulrich; Lehmann, Hanna (2003): Marktorientierte Investitionsrechnung bei Unsicherheit, Flexibilität und Irreversibilität. Eine Systematik der Bewertungsverfahren. In Ulrich Hommel, Martin Scholich, Philipp Baecker (Eds.): Reale Optionen. Konzepte, Praxis und Perspektiven strategischer Unternehmensfinanzierung. Berlin [u.a.]: Springer [u.a.], pp. 15–35.

Baldwin, Robert; Cave, Martin E.; Lodge, Martin (2012): Understanding regulation. Theory, strategy, and practice. 2nd ed. Oxford [etc.]: Oxford University Press.

Balikcioglu, Metin; Fackler, Paul L.; Pindyck, Robert S. (2011): Solving optimal timing problems in environmental economics. In *Resource and Energy Economics* 33 (3), pp. 761–768.

Bamberg, Günter; Coenenberg, Adolf Gerhard; Krapp, Michael (2012): Betriebswirtschaftliche Entscheidungslehre. 15. Aufl. München: Vahlen, Franz.

Bashiri, Ali; Lawryshyn, Yuri (2017): A Stochastic Supply/Demand Model for Storable Commodity Prices. Boston (21st Annual International Conference on Real Options). Available online at http://realoptions.org/openconf2017/data/papers/36.pdf, checked on 11/9/2018.

Baumüller, F.; Schlessing, J.; Strasser, P. (1987): Primärmassnahmen zur NOx-Minderung in erdgas-, öl- und steinkohlebefeuerten Dampferzeugern im Grosskraftwerk Manhheim. In *VGB Kraftwerkstechnik* 67 (5), pp. 498–505.

Beckmann, Michael (2011): Beschreibung unterschiedlicher Techniken und deren Entwicklungspotentiale zur Minderung von Stickstoffoxiden im Abgas von Abfallverbrennungsanlagen und Ersatzbrennstoff-Kraftwerken hinsichtlich Leistungsfähigkeit, Kosten und Energieverbrauch. Edited by Umweltbundesamt. Technische Universität Dresden. Available online at http://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/4196.pdf, checked on 11/9/2018.

Bekefi, Tamara; Epstein, Marc J. (2006): Integrating social and political risk into management decision-making: Society of Management Accountants of Canada and The American Institute of Certified Public Accountants. Available online at http://www.cimaglobal.com/Documents/ImportedDocuments/Tech_MAG_Integrating_Social_Political_Risks_Sept06.pdf, checked on 11/9/2018.

Bellman, Richard Ernest (2013): Dynamic programming. Mineola, N.Y.: Dover.

Bertsch, Valentin (2008): Uncertainty handling in multi-attribute decision support for industrial risk management. Karlsruhe: Univ.-Verl. Karlsruhe.

Betge, Peter (1995): Investitionsplanung. Methoden – Modelle – Anwendungen. 2., aktualisierte und erweiterte Auflage. Wiesbaden: Gabler Verlag.

Bikhchandani, Sushil; Hirshleifer, Jack; Riley, John G. (2013): The analytics of uncertainty and information. Second Edition. New York: Cambridge University Press (Cambridge surveys of economic literature).

Biofuelwatch (2014): Power Plant Emissions during Startup and Shutdown (Biofuelwatch briefing). Available online at http://www.biofuelwatch.org.uk/docs/Power-Station-Start-up-Emissions.pdf, checked on 11/9/2018.

Birge, John R. (2000): Option Methods for Incorporating Risk into Linear Capacity Planning Models. In *M&SOM* 2 (1), pp. 19–31. DOI: 10.1287/msom.2.1.19.23269.

Bivens, R. J. (2002): Startup and Shutdown NOx Emissions from Combined-Cycle Combustion Turbine Units. Chicago (EPRI CEM User Group Meeting). Available online at http://www.rmb-consulting.com/papers/SUSD%20Chicago%20Paper.pdf, checked on 11/9/2018.

Black, Fischer; Scholes, Myron (1973): The Pricing of Options and Corporate Liabilities. In *Journal of Political Economy* (81), pp. 637–654, checked on 4/1/2015.

Blakeslee, C. E.; Burbach, H. E. (1973): Controlling NOx Emissions From Steam Generators. In *Journal of the Air Pollution Control Association* 23 (1), pp. 37–42. DOI: 10.1080/00022470.1973.10469746.

Blyth, William; Bradley, Richard; Bunn, Derek; Clarke, Charlie; Wilson, Tom; Yang, Ming (2007): Investment risks under uncertain climate change policy. In *Energy Policy* 35 (11), pp. 5766–5773. DOI: 10.1016/j.enpol.2007.05.030.

Böcher, Michael (2012): A theoretical framework for explaining the choice of instruments in environmental policy. In *Forest Policy and Economics* 16, pp. 14–22. DOI: 10.1016/j.forpol.2011.03.012.

Böcher, Michael; Töller, Annette Elisabeth (2007): Instrumentenwahl und Instrumentenwandel in der Umweltpolitik. Ein theoretischer Erklärungsrahmen. In *Politische Vierteljahresschrift* (39), pp. 299–322.

Boomsma, Trine Krogh; Meade, Nigel; Fleten, Stein-Erik (2012): Renewable energy investments under different support schemes: A real options approach. In *European Journal of Operational Research* 220 (1), pp. 225–237. DOI: 10.1016/j.ejor.2012.01.017.

Brach, Marion A. (2003): Real options in practice. Hoboken, N.J.: John Wiley & Sons (Wiley finance series).

Brandwood, Roger (2018): Forecasting the Future of Coal Fired Power Stations to Prepare Successfully for Forthcoming Change. ExPPERTS Europe Conference. Wroclaw, Poland, 9/27/2018.

Breun, Patrick (2016): Ein Ansatz zur Bewertung klimapolitischer Instrumente am Beispiel der Metallerzeugung und -verarbeitung. Karlsruhe, Baden: KIT Scientific Publishing (Produktion und Energie, 11).

Breun, Patrick; Comes, Tina; Doll, Claus; Fröhling, Magnus; Hiete, Michael (2012): National Integrated Assessment Modelling zur Bewertung umweltpolitischer Instrumente. Entwicklung des otello-Modellsystems und dessen Anwendung auf die Bundesrepublik Deutschland. Karlsruhe: KIT Scientific Publishing (Produktion und Energie, 1).

Buchner, Barbara (2007): Policy Uncertainty, Investment and Commitment Periods. OECD/IEA. Paris. Available online at https://webstore.iea.org/policy-uncertainty-investment-and-commitment-periods, checked on 11/9/2018.

Bunbury, H. M. (1925): Die Chemie des Holzes. In H. M. Bunbury (Ed.): Die trockene Destillation des Holzes. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 35–55.

Busse von Colbe, Walther; Laßmann, Gert; Witte, Frank (2015): Investitionstheorie und Investitionsrechnung. Berlin, Heidelberg: Springer Berlin Heidelberg.

Buurman, Joost; Babovic, Vladan (2017): Adaptation Pathways and Real Options Analysis. An approach to deep uncertainty in climate change adaptation policies. In *Policy and Society* 35 (2), pp. 137–150. DOI: 10.1016/j.polsoc.2016.05.002.

CAGI (2018): Pressure Drop Cost Calculator. Compressed Air & Gas Institute. Available online at http://cagi.org/files/Cost_of_pressure_drop_calculation-n.xlsm, checked on 8/22/2018.

Callan, Scott J.; Thomas, Janet M. (2013): Environmental Economics and Management. Theory, policy and management. 6 ed. Mason, OH: South-western college Publishing.

Campbell, Wallace (2013): Valuation of timberland under price uncertainty. Dissertation. Clemson University.

Carmona, René; Fehr, Max; Hinz, Juri; Porchet, Arnaud (2010): Market Design for Emission Trading Schemes. In *SIAM Rev.* 52 (3), pp. 403–452. DOI: 10.1137/080722813.

Carnegie Mellon University (2018): Integrated Environmental Control Model. IECM. Department of Engineering & Public Policy. Available online at http://www.cmu.edu/epp/iecm/index.html, checked on 11/9/2018.

Carr, Peter P.; Jarrow, Robert A. (1990): The Stop-Loss Start-Gain Paradox and Option Valuation. A New Decomposition into Intrinsic and Time Value. In *Rev. Financ. Stud.* 3 (3), pp. 469–492. DOI: 10.1093/rfs/3.3.469.

Chalmers, Hannah; Gibbins, Jon (2007): Initial evaluation of the impact of post-combustion capture of carbon dioxide on supercritical pulverised coal power plant part load performance. In *Fuel* 86 (14), pp. 2109–2123. DOI: 10.1016/j.fuel.2007.01.028.

Chauvel, Alain; Fournier, Gilles; Raimbault, Claude (2003): Manual of Process Economic Evaluation. New, rev. and expanded ed. Paris: Editions Technip (Institut français du pétrole publications).

ChinaFAQs (2012): China Adopts World-Class Pollutant Emissions Standards for Coal Power Plants. Edited by World Resources Institute. Available online at http://www.neec.no/wp-content/uploads/ChinaFAQs.pdf, checked on 11/9/2018.

Chronopoulos, Georgios (2016): The European Best Available Techniques (BAT) approach. Workshop to promote the understanding and implementation of BAT across the entire UNECE region with focus on countries in the EECCA region. European IPPC Bureau. Berlin, 2016.

Chronopoulos, Michail; Hagspiel, Verena; Fleten, Stein-Erik (2016): Stepwise Green Investment under Policy Uncertainty. In *EJ* 37 (4). DOI: 10.5547/01956574.37.4.mchr.

Cichanowicz, J. E. (2004): Why are SCR costs still rising? In *Power* 3 (148), pp. 32–40.

Cichanowicz, J. E. (2010): Current Capital Cost and Cost-Effectiveness of Power Plant Emissions Control Technologies. Prepared for Utility Air Regulatory Group. Utility Air Regulatory Group.

Comes, Tina (2011): Decision Maps for Distributed Scenario-Based Multi-Criteria Decision Support. Dissertation. Karlsruhe Institute of Technology, Karlsruhe. Institute for Industrial Production.

Coombs, K. A.; Crilley, J. S.; Shilling, M.; Higgins, B. (2004): SCR Levels of NOx Reduction with ROFA and Rotamix (SNCR) at Dynegy's Vermilion Power Station. In *2004 Stack Emissions Symposium*.

Cox, John; Ross, Stephen; Rubinstein, Mark (1979): Option Pricing: A Simplified Approach. In *Journal of Financial Economics* 7 (3), pp. 229–263.

CSE (2016): New envirnmental norms for the power sector. Proceedings and Recommendations of the Stakeholder Workshop Organized by CSE. Centre for Science and Environment. New Delhi, India. Available online at https://cdn.cseindia.org/attachments/0.65248400_1516790432_new-environmental-norms-report.pdf, checked on 10/11/2018.

Department of the Environment and Department of Health (2014): Regulatory Impact Analysis Statement. Vol. 148. Edited by Her Majesty the Queen in Right of Canada. Ottawa (Canada Gazette Part I, No. 23). Available online at http://www.gazette.gc.ca/rp-pr/p1/2014/2014-06-07/pdf/g1-14823.pdf, checked on 11/9/2018.

Detert, Neal; Kotani, Koji (2013): Real options approach to renewable energy investments in Mongolia. In *Energy Policy* 56, pp. 136–150. DOI: 10.1016/j.enpol.2012.12.003.

Dixit, Avinash K.; Pindyck, Robert S. (1994): Investment under uncertainty. Princeton, N.J.: Princeton University Press.

Dong, Nigel S. (2010): Reducing carbon-in-ash. In *Profiles* 10 (8).

Ebeling, Norbert (1999): Abluft und Abgas. Reinigung und Überwachung. Weinheim, Chichester: Wiley-VCH (Praxis des technischen Umweltschutzes).

EEC (1988): Council Directive 88/609/EEC of 24 November 1988 on the limitation of emissions of certain pollutants into the air from large combustion plants. In *OJ L 336* 7.12.1988, pp. 14–18.

Eeckhoudt, Louis; Gollier, Christian; Schlesinger, Harris (2005): Economic and financial decisions under risk. Princeton, N.J.: Princeton University Press.

EGTEI secretariat (2014): Estimation of costs of reduction techniques for LCP. Examples of results obtained. Expert Group on Techno-Economic Issues. Available online at http://tftei.citepa.org/images/files/2014-10-08/3-EGTEI_cost_calc_Examples-30-09-2014.pdf, checked on 11/9/2018.

Elberfeld, Walter; Nti, Kofi O. (2004): Oligopolistic Competition and New Technology Adoption under Uncertainty. In *JEcon* 82 (2). DOI: 10.1007/s00712-003-0048-4.

Epstein, Marc J.; Rejc Buhovac, Adriana (2014): Making sustainability work. Best practices in managing and measuring corporate social, environmental, and economic impacts. Second edition, completely revised and updated. San Francisco: Berrett-Koehler Publishers.

Eryilmaz, Derya; Homans, Frances R. (2016): How does uncertainty in renewable energy policy affect decisions to invest in wind energy? In *The Electricity Journal* 29 (3), pp. 64–71. DOI: 10.1016/j.tej.2015.12.002.

EU (2001): Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants. In *OJ L 309* 27.11.2001, pp. 1–21.

EU (2008): Directive 2008/1/EC of the European Parliament and of the Council of 15 January 2008 concerning integrated pollution prevention and control (Codified version). In *OJ L 24* 29.01.2008, pp. 8–29.

EU (2010): Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control). In *OJ L 334* 17.12.2010, pp. 17–119.

European Commission (2006): Reference Document on Best Available Techniques for Large Combustion Plants. Integrated Pollution Prevention and Control. Available online at http://eippcb.jrc.ec.europa.eu/reference/BREF/lcp_bref_0706.pdf, checked on 11/9/2018.

European Commission (2010): Economic analysis to support an Impact Assessment of the possible establishment of EU-wide emissions trading of NOx and/or SO2. With assistance of Ben Grebot, Rohit Mistry. Edited by Entec UK Limited. Available online at https://circabc.europa.eu/webdav/CircaBC/env/ippc_rev/Library/emissions_trading/strakeholder_february/Terms%20of%20reference%202nd%20ET%20study%20NOx-SO2%20(CIRCA).pdf, checked on 11/9/2018.

European Commission (2013): The EU emissions trading scheme system (EU ETS). 2013 ed. Luxembourg: European Union Publications Office.

European Commission (2018): Website Energy Department. Available online at https://ec.europa.eu/energy/en, checked on 8/7/2018.

European Energy Exchange AG (2018): EU Emission Allowances. Leipzig. Available online at https://www.eex.com/en/market-data/environmental-markets/spot-market/european-emission-allowances#!/2018/10/19, checked on 10/21/2018.

European Environment Agency (2018a): Air pollutant emissions data viewer (Gothenburg Protocol, LRTAP Convention) 1990-2016. Copenhagen, Denmark. Available online at https://www.eea.europa.eu/data-and-maps/dashboards/air-pollutant-emissions-data-viewer-1, checked on 11/15/2018.

European Environment Agency (2018b): European Pollutant Release and Transfer Register. EEA. Denmark. Available online at http://prtr.ec.europa.eu/#/home, checked on 1/15/2018.

Everard, Mark (2017): Ecosystem Services. Key Issues. London: Taylor and Francis (Key Issues in Environment and Sustainability).

Ewald, Christian-Oliver; Yang, Zhaojun (2008): Utility based pricing and exercising of real options under geometric mean reversion and risk aversion toward idiosyncratic risk. In *Mathematical Methods of Operations Research* 68 (1), pp. 97–123. DOI: 10.1007/s00186-007-0190-9.

Faber Burner Company (2018): Emissions Conversions Calculater. Available online at http://www.faberburner.com/resource-center/conversion-charts/emissions-conversions-calculator/, checked on 8/24/2018.

Falcone Miller, S.; Miller, B. G. (2010): Advanced flue gas cleaning systems for sulfur oxides (SOx), nitrogen oxides (NOx) and mercury emissions control in power plants. In Dermot J. Roddy (Ed.): Advanced power plant materials, design and technology. Cambridge: Woodhead Publishing Ltd, pp. 187–215.

Farwick, H.; Rummenhohl, V. (1993): SCR-Katalysatoren. Fünf Jahre Betriebserfahrung mit SCR-Anlagen in allen Schaltungen und daraus entwickelte Konsequenzen und Maßnahmen. In *VGB Kraftwerkstechnik* 73 (5), pp. 437–441.

Fenimore, C. P. (1979): Studies of fuel-nitrogen species in rich flame gases. In *Symposium (International) on Combustion* 17 (1), pp. 661–670. DOI: 10.1016/S0082-0784(79)80065-X.

Fernandes, Bartolomeu; Cunha, Jorge; Ferreira, Paula (2011): The use of real options approach in energy sector investments. In *Renewable and Sustainable Energy Reviews* 15 (9), pp. 4491–4497. DOI: 10.1016/j.rser.2011.07.102.

Firger, Daniel M. (2015): The potential of international climate change law to mobilise low-carbon foreign direct investment. In Pierre-Marie Dupuy, Jorge E. Vinuaels (Eds.): Harnessing foreign investment to promote environmental protection. Incentives and Safeguards. Cambridge: Cambridge Univ Press, pp. 176–205.

Fisher, Jeffery E. (2002): Comparison of Urea-Based Ammonia to Liquid Ammonia Systems for NOx Reduction Applications. In *Electric Energy* (11/12).

Flyvbjerg, Bent; Sunstein, Cass R. (2015): The Principle of the Malevolent Hiding Hand; or, the Planning Fallacy Writ Large. In *Social Research* Forthcoming, 9/2/2015.

Fox, Phyllis (2011): Revised BART Cost Effectiveness Analysis for Tail-End Selective Catalytic Reduction at the Basin Electric Power Cooperative Leland Olds Station Unit 2. Final Report. prepared for U.S. Environmental Protection Agency Region 8.

Fraunhofer ISE (2018): Energy Charts. EPEX data. Available online at https://www.energy-charts.de/price_avg_de.htm?year=2017&price=nominal&period=annual, checked on 11/9/2018.

Friedemann, Christian (1998): Umweltorientierte Investitionsplanung. Wiesbaden: Gabler (Betriebswirtschaftliche Forschung zur Unternehmensführung, 34).

Friedl, Gunther (2007): Real options and investment incentives. Berlin, New York: Springer.

Friedl, Gunther; Hofmann, Christian; Pedell, Burkhard (2013): Kostenrechnung. Eine entscheidungsorientierte Einführung. 2. Aufl. München: Vahlen, Franz.

Fuss, Sabine; Johansson, Daniel J.A.; Szolgayova, Jana; Obersteiner, Michael (2009): Impact of climate policy uncertainty on the adoption of electricity generating technologies. In *Energy Policy* 37 (2), pp. 733–743. DOI: 10.1016/j.enpol.2008.10.022.

Geldermann, Jutta (2014): Anlagen- und Energiewirtschaft. Kosten- und Investitionsschätzung sowie Technikbewertung von Industrieanlagen. München: Vahlen.

Goldring, John; Riley, Gerry (2016): Primary NOx reduction technology development. The road to IED compliance. In *VGB PowerTech* (11), pp. 64–71.

Götze, Uwe (2008): Investitionsrechnung. Modelle und Analysen zur Beurteilung von Investitionsvorhaben. [Online-Ausg. der] 6., durchges. und aktualisierten [gedr.] Aufl. Berlin, Heidelberg: Springer (Springer-Lehrbuch).

Götze, Uwe; Northcott, Deryl; Schuster, Peter (2015): Investment appraisal. Methods and models. Second edition: Springer Verlag (Springer texts in business and economics).

Gurjar, B. R.; Molina, Luisa T.; Ojha, C. Shekhar P. (Eds.) (2010): Air pollution. Health and environmental impacts. Boca Raton: CRC Press.

Hahn, Joachim Tobias (2013): Option Pricing Using Artificial Neural Networks: An Australian Perspective. Dissertation. Bond University, Robina, Australia. Faculty of Business.

Hambrick, Donald C.; Fredrickson, James W. (2001): Are you sure you have a strategy? In *Academy of Management Executive* 15 (4), pp. 48–59.

Hassani, Bertrand (2016): Scenario analysis in risk management. Theory and practice in finance. Cham: Springer International Publishing.

He, Yizhi (2007): Real options in the energy markets. Enschede: University of Twente. Available online at https://research.utwente.nl/files/6039503/thesis_He.pdf, checked on 11/9/2018.

Heide, Bernd von der (2008): SNCR Process - Best Available Technology for NOx Reduction in Waste To Energy Plants. POWER-GEN Europe. Mehldau & Steinfath Umwelttechnik GmbH. Milan, 2008.

Heide, Bernd von der (2012a): Ist das SNCR-Verfahren noch Stand der Technik? In Karl J. Thomé-Kozmiensky, Michael Beckmann (Eds.): Energie aus Abfall. Neuruppin: TK Verlag Karl Thomé Kozmiensky (9).

Heide, Bernd von der (2012b): Möglichkeiten und Grenzen der SNCR-Verfahren. In Karl J. Thomé-Kozmiensky, Michael Beckmann (Eds.): Energie aus Abfall. Neuruppin: TK Verlag Karl Thomé Kozmiensky (9), pp. 601–627.

Helsinki Commission (2005): Airborne nitrogen loads to the Baltic Sea. Baltic Marine Environment Protection Commission. Helsinki. Available online at http://www.helcom.fi/Lists/Publications/Airborne%20nitrogen%20 loads%20to%20the%20Baltic%20Sea.pdf, checked on 11/13/2018.

Hering, Thomas (2008): Investitionstheorie. 3., überarb. und aktualisierte Aufl. München: Oldenbourg.

Himes, R. (2004): SNCR Guidelines Update. Electric Power Research Institute. Palo Alto. Available online at https://publicdownload.epri.com/PublicDownload.svc/product=000000 000001004727/type=Product, checked on 11/9/2018.

Hirschman, Albert O. (1967): Development Projects Observed. Washington, DC: Brookings Inst.

Hodgson, Ian (2018): European Commission: A legislative follow up. ExPPERTS Europe Conference. Wroclaw, Poland, 9/26/2018.

Hoffmann, Volker H. (2007): EU ETS and Investment Decisions. In *European Management Journal* 25 (6), pp. 464–474. DOI: 10.1016/j.emj.2007.07.008.

Hofmann, Erik; Maucher, Daniel; Hornstein, Jens; den Ouden, Rainer (2012): Capital Equipment Purchasing. Optimizing the Total Cost of CapEx Sourcing. Berlin, Heidelberg: Springer Berlin Heidelberg (Professional Supply Management, 2).

Hommel, Ulrich; Lehmann, Hanna (2001): Die Bewertung von Investitionsprojekten mit dem Realoptionsansatz – Ein Methodenüberblick. In Ulrich Hommel, Martin Scholich (Eds.): Realoptionen in der Unternehmenspraxis. Wert schaffen durch Flexibilität. Berlin [u.a.]: Springer, pp. 113–129.

Hommel, Ulrich; Pritsch, G. (1999): Investitionsbewertung und Unternehmensführung mit dem Realoptionsansatz. In Ann-Kristin Achleitner, Georg F. Thoma (Eds.): Handbuch Corporate Finance. Köln: Deutscher Wirtschaftsdienst, pp. 1–67.

Hoskins, Bill (2003): Uniqueness of SCR Retrofits Translates into Broad Cost Variations. In *POWER Engineering* 5 (107), pp. 25–30.

Hubbard, Douglas W. (2009): The failure of risk management. Why it's broken and how to fix it. Hoboken, N.J.: Wiley.

Hugonnier, Julien N.; Morellec, Erwan (2003): Risk Aversion and Real Options. In *SSRN Journal. DOI:* 10.2139/ssrn.422600.

Hull, John (2012): Options, futures, and other derivatives. 8th ed. Boston: Prentice Hall.

Hundt, Matthias (2015): Investitionsplanung unter unsicheren Einflussgrößen. Thermische Kraftwerke als Realoptionen. Wiesbaden: Springer Gabler (SpringerLink : Bücher).

Ibe, Oliver C. (2013): Markov processes for stochastic modeling. Second edition. Amsterdam, London: Elsevier (Elsevier insights).

ICAC (2009): Selective catalytic reduction (SCR) control of NOx emissions from fossil fuel-fired electric power plants. White Paper. Institute of Clean Air Companies NOx Control Technical Division. Available online at https://c.ymcdn.com/sites/icac.site-ym.com/resource/resmgr/Standards_WhitePapers/SCR_WhitePaper_final_2009.pdf, checked on 11/9/2018.

ICAC SNCR Committee (2008): Selective Non-Catalytic Reduction (SNCR) for Controlling NOx Emissions. White Paper. Institute of Clean Air Companies. Available online at https://c.ymcdn.com/sites/icac.site-ym.com/resource/resmgr/Standards_WhitePapers/SNCR_Whitepaper_Final.pdf, checked on 11/9/2018.

IEA Clean Coal Centre (2017): Selective non-catalytic reduction (SNCR) for NOx control (Technology Collaboration Programme (TCP)). Available online at https://www.iea-coal.org/selective-non-catalytic-reduction-sncr-for-nox-control/, checked on 11/9/2018.

IMF (2018): Indien: Inflationsrate von 2008 bis 2018 (gegenüber dem Vorjahr). International Monetary Fund. Available online at https://de.statista.com/statistik/daten/studie/170812/umfrage/inflationsrate-in-indien/, checked on 10/19/2018.

Indo-German AHK (2018): Factsheet Indien. Allgemeine Energiemarkt-informationen. Available online at https://www.german-energy-solutions.de/GES/Redaktion/DE/Publikationen/Kurzinformationen/2018/fs_indien_2018.pdf?__blob=publicationFile&v=3, checked on 10/11/2018.

Insley, Margaret; Rollins, Kimberly (2005): On Solving the Multirotational Timber Harvesting Problem with Stochastic Prices. A Linear Complementarity Formulation. In *Am J Agricultural Economics* 87 (3), pp. 735–755. DOI: 10.1111/j.1467-8276.2005.00759.x.

Insley, Margaret C. (2003): On the Option to Invest in Pollution Control under a Regime of Tradable Emissions Allowances. In *The Canadian Journal of Economics* 36 (4), pp. 860–883. DOI: 10.2307/3131804.

Institute of Management Accountants (1996): Practices and techniques. Tools and techniques of environmental accounting for business decisions. Montvale, New Jersey: Institute of Management Accountants (Statements on Management Accounting, 4Z).

International Energy Agency (2007): Climate Policy. Uncertainty and Investment Risk. Paris. Available online at https://www.iea.org/publications/freepublications/publication/Climate_Policy_Uncertainty.pdf, checked on 11/9/2018.

International Energy Agency (2014): World Energy Investment Outlook. Special Report. Edited by OECD/IEA. Paris. Available online at https://www.iea.org/publications/freepublications/publication/WEIO2014.pdf, checked on 11/9/2018.

International Finance Corporation (2008): Environmental, Health, and Safety Guidelines for Thermal Power Plants. World Bank Group. Available online at http://www.ifc.org/wps/wcm/connect/dfb6a60048855a21852cd76a6515bb18/FINAL_Thermal%2BPower.pdf?MOD=AJPERES&id=1323162579734, checked on 11/9/2018.

Jaber, Mohamad Y. (Ed.) (2011): Learning curves. Theory, models, and applications. Boca Raton: CRC Press (Industrial innovation series, 21).

Jaffe, Adam B.; Newell, Richard G.; Stavins, Robert N. (2003): Technological change and the Environment. In : Environmental Degradation and Institutional Responses, vol. 1: Elsevier (Handbook of Environmental Economics), pp. 461–516.

Jenkins, Scott (1998-2017): Current Economic Trends. In *Chemical Engineering* several editions.

Jensen-Holm, Hans; Thøgersen, Joakim Reimer; White, Nathan (2009): Impact of Biomass Co-Combustion on SCR DeNOx Operation. In *WPCA News* 16, pp. 7–17.

Jonge, Lex de: NOx emission trading in the Netherlands. Lessons learned. Ministry of Infrastructure and the Environment. Available online at https://www.thepmr.org/system/files/documents/PA4_Netherlands_Nox_0.pdf, checked on 5/29/2018.

Joos, Franz (2007): Technische Verbrennung. Verbrennungstechnik, Verbrennungsmodellierung, Emissionen. 1. Aufl. Berlin: Springer.

Julio, Brandon; Yook, Youngsuk (2012): Political Uncertainty and Corporate Investment Cycles. In *The Journal of Finance* 67 (1), pp. 45–83.

Kather, A.; Brüggemann, H.; Epple, B. (1997): NOx-arme Steinkohlefeuerung für Großdampferzeuger. In *VGB Kraftwerkstechnik* 77 (6), pp. 470–475.

Kather, A.; Gellert, S.; Woltersdorf, N.; Roeder, V.; Paschke, B.; Everts, B. et al. (2013): Innovative Techniken - Beste verfügbare Technik in ausgewählten Sektoren. Teilvorhaben 01: Großfeuerungsanlagen (Revision des BVT-Merkblattes ab 2010). Institut für Energietechnik, TUHH. Hamburg.

Kelly, B.; Pástor, L.; Veronesi, P. (2016): The Price of Political Uncertainty. Theory and Evidence from the Option Market. In *The Journal of Finance* 71 (5), pp. 2417–2480. DOI: 10.1111/jofi.12406.

Klingelhöfer, Heinz Eckart (2006): Finanzwirtschaftliche Bewertung von Umweltschutzinvestitionen. 1. Aufl. Wiesbaden: Deutscher Universitäts-Verlag (Gabler Edition Wissenschaft: Moderne Finanzwirtschaft & Unternehmensbewertung).

Knight, Frank H. (1921): Risk, Uncertainty and Profit. Boston: Houghton Mifflin Company.

Kodukula, Prasad; Papudesu, Chandra (2006): Project valuation using real options. A practitioner's guide. Ft. Lauderdale, Fla.: J. Ross Pub.

Kokopeli, P.; Schreifels, J.; Forte, R. (2013): Assessment of startup period at coal-fired electric generating units. U.S. Environmental Protection Agency, Office of Air and Radiation.

Kolar, Jörgen (1990): Stickstoffoxide und Luftreinhaltung. Grundlagen, Emissionen, Transmission, Immissionen, Wirkungen ; mit 102 Tabellen. Berlin: Springer.

Könings, Melvin (2003): Emission trading – why State aid is involved: NOx trading scheme (Competition Policy Newsletter, 3). Available online at http://ec.europa.eu/competition/publications/cpn/2003_3_77.pdf, checked on 11/9/2018.

Kou, S. G. (2002): A Jump-Diffusion Model for Option Pricing. In *Management Science* 48 (8), pp. 1086–1101.

Krishnan, Ravi (2016): India's new emissions rules: challenges and opportunities. Edited by Modern Power Systems. Available online at http://www.modernpowersystems.com/features/featureindias-new-emissions-rules-challenges-and-opportunities-5694187/, checked on 10/11/2018.

Krug, Bernd (2015): Capital asset pricing model. Statistische inferenz. Hamburg: Diplomica Verlag.

Kruschwitz, Lutz (2014): Investitionsrechnung. 14. Aufl. Berlin: De Gruyter.

Krysiak, Frank C. (2011): Environmental regulation, technological diversity, and the dynamics of technological change. In *Journal of Economic Dynamics and Control* 35 (4), pp. 528–544. DOI: 10.1016/j.jedc.2010.12.004.

Lambrecht, Bart M. (2017): Real options in finance. In *Journal of Banking & Finance* 81, pp. 166–171. DOI: 10.1016/j.jbankfin.2017.03.006.

Lammel, G.; Graßl, H. (1995): Greenhouse effect of NOX. In *Environmental science and pollution research international* 2 (1), pp. 40–45. DOI: 10.1007/BF02987512.

Lange, C.; Ukena, H. (1996): Integrierte Investitionsplanung und -kontrolle im Rahmen eines betrieblichen Umweltschutz-Controllingsystems. In *Zeitschrift für angewandte Umweltforschung* 9, pp. 67–85.

Langer, Magnus Jesko (2015): Key instruments of private environmental finance: funds, project finance and market mechanisms. In Pierre-Marie Dupuy, Jorge E. Vinuaels (Eds.): Harnessing foreign investment to promote environmental protection. Incentives and Safeguards. Cambridge: Cambridge Univ Press, pp. 131–175.

Lani, Bruce W.; Feeley, Thomas J.; Miller, Charles E.; Carney, Barbara A.; Murphy, James T. (2008): DOE/NETL's NOx Emissions Control R&D Program. Bringing Advanced Technology to the Marketplace. U.S. Department of Energy, National Energy Technology Laboratory. Available online at http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/iep-NOx-r-d-program-brochure-v-3-0408.pdf, checked on 11/9/2018.

Large, Rudolf (2009): Strategisches Beschaffungsmanagement. Eine praxisorientierte Einführung. Mit Fallstudien. 4th ed. Wiesbaden: Betriebswirtschaftlicher Verlag Gabler (Lehrbuch).

Laurikka, Harri; Koljonen, Tiina (2006): Emissions trading and investment decisions in the power sector—a case study in Finland. In *Energy Policy* 34 (9), pp. 1063–1074. DOI: 10.1016/j.enpol.2004.09.004.

Laux, Helmut; Gillenkirch, Robert M.; Schenk-Mathes, Heike Yasmin (2014): Entscheidungstheorie. 9., vollst. überarb. Aufl. 2014. Berlin, Heidelberg: Springer Gabler (Springer-Lehrbuch).

Lecomte, Thierry; Neuwahl, Frederik; Canova, Michele; Pinasseau, Antoine; Jankov, Ivan; Brinkmann, Thomas et al. (2017): Best Available Techniques (BAT) reference document for large combustion plants. Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control). Luxembourg: Publications Office (EUR, Scientific and technical research series, 28836).

Lee, Shun-Chung (2011): Using real option analysis for highly uncertain technology investments: The case of wind energy technology. In *Renewable and Sustainable Energy Reviews* 15 (9), pp. 4443–4450. DOI: 10.1016/j.rser.2011.07.107.

Lee, Shun-Chung; Shih, Li-Hsing (2010): Renewable energy policy evaluation using real option model — The case of Taiwan. In *Energy Economics* 32, pp. S67–S78. DOI: 10.1016/j.eneco.2010.04.010.

Lenntech (2018): Parts Per Million (ppm) Converter for Gases. Available online at https://www.lenntech.com/calculators/ppm/converter-parts-per-million.htm, checked on 8/24/2018.

Lenz, W. (1987): Dampferzeugungsanlagen. Dubbel. 16th ed. Berlin: Springer.

Leslie, Keith J.; Michaels, Max P. (1997): The real power or real options (The McKinsey Quarterly, 3). Available online at https://faculty.fuqua.duke.edu/~charvey/Teaching/BA456_2006/McK97_3.pdf, checked on 11/9/2018.

Linnerud, Kristin; Andersson, Ane Marte; Fleten, Stein-Erik (2014): Investment timing under uncertain renewable energy policy. An empirical study of small hydropower projects. In *Energy* 78, pp. 154–164. DOI: 10.1016/j.energy.2014.09.081.

Lodewijks, Pieter; Pieper, Hannes; van Wortswinkel, Luc (2013): Reducing air pollution from electricity-generating large combustion plants in the European Union. An assessment of potential emission reductions of NOX, SO2 and dust. Luxembourg: Publications Office (EEA Technical Report, 9/2013).

Löffler, G.; Sieber, R.; Harasek, M.; Hofbauer, H.; Hauss, R.; Landauf, J. (2006): NOx formation in natural gas combustion—a new simplified reaction scheme for CFD calculations. In *Fuel* 85 (4), pp. 513–523. DOI: 10.1016/j.fuel.2005.07.012.

Longstaff, Francis A.; Schwartz, Eduardo S. (2001): Valuing American Options by Simulation. A Simple Least-Squares Approach. In *Review of Financial Studies* 14 (1), pp. 113–147. DOI: 10.1093/rfs/14.1.113.

Lutz, Björn (2010): Pricing of Derivatives on Mean-Reverting Assets. Berlin, Heidelberg: Springer Berlin Heidelberg (630).

Maier, Herwig (2010): SCR Catalyst Management - More than 20 Years of Experience. In *VGB PowerTech* 4, pp. 44–47.

Marano, Mark; Sharp, George (2006): Estimating SCR installation costs. American Electric Power, EUCG Fossil Productivity Committee. Available online at https://www.powermag.com/estimating-scr-installation-costs/, checked on 11/9/2018.

Marathe, Rahul R.; Ryan, Sarah M. (2005): On The Validity of The Geometric Brownian Motion Assumption. In *The Engineering Economist* 50 (2), pp. 159–192. DOI: 10.1080/00137910590949904.

Marlowe, Ian; King, Katie; Boyd, Richard; Bouscaren, Rémy; Pacyna, Joszef (1999): Guidelines for defining and documenting data on costs of possible environmental protection measures. European Environment Agency. Copenhagen (Technical report, 27).

Maxwell, Christian; Davison, Matt (2015): Real Options with Regulatory Policy Uncertainty. In René Aïd, Michael Ludkovski, Ronnie Sircar (Eds.): Commodities, energy and environmental finance, vol. 74. New York: Springer (Fields Institute Communications, v. 74), pp. 239–273.

Mayer, C.; Müller, A.-K.; Fröhling, M.; Schultmann, F. (2015): Early Stage Investment and Cost Calculation Methodologies for NOx Reduction Measures in Large Combustion Plants. In B. F. Giannetti, C.M.V.B. Almeida, F. Agostinho, S. H. Bonilla (Eds.): Cleaner Production Towards a Sustainable Transition. Proceedings of the 5th International Workshop Advances in Cleaner Production. Sao Paulo, Brazil, May 20th to 22nd.

Mayer, Carmen; Breun, Patrick; Schultmann, Frank (2017): Considering risks in early stage investment planning for emission abatement technologies in large combustion plants. In *Journal of Cleaner Production* 142, pp. 133–144. DOI: 10.1016/j.jclepro.2016.05.089.

Mayer, Carmen; Lanzrath, Natalie; Breun, Patrick; Schultmann, Frank (2016): A Comparison of International Nitrogen Oxide Emission Regulation for the Energy Sector. In João Joanaz de Melo, Antje Disterheft, Sandra Caeiro, Rui F. Santos, Tomás B. Ramos (Eds.): Proceedings of the 22nd Annual International Sustainable Development Research Society Conference. Rethinking Sustainability Models and Practices: Challenges for the New and Old World Contexts, vol. 3. Lisbon, July. 3 volumes. Lisbon, pp. 394–406.

Mayer, Carmen; Schultmann, Frank (2017): Real Option Valuation Methods and their Application for Emission Abatement Investments. Boston. Available online at http://www.realoptions.org/openconf2017/data/papers/12.pdf, checked on 11/8/2018.

McMahon, B. (2006): Catalyst regeneration: The business case. In *Power* (02).

Meinke, Sebastian (2014): Modellierung thermischer Kraftwerke vor dem Hintergrund steigender Dynamikanforderungen aufgrund zunehmender Windenergie- und Photovoltaikeinspeisung. Universität Rostock, Fakultät für Maschinenbau und Schiffstechnik, Dissertation. Available online at http://nbn-resolving.de/urn:nbn:de:gbv:28-diss2014-0090-9, checked on 11/9/2018.

Menon, Anil; Varadarajan, P. Rajan (1992): A Model of Marketing Knowledge Use within Firms. In *Journal of Marketing* 56 (4), p. 53. DOI: 10.2307/1251986.

Merton, Robert C. (1976): Option pricing when underlying stock returns are discontinuous. In *Journal of Financial Economics* 3 (1-2), pp. 125–144. DOI: 10.1016/0304-405X(76)90022-2.

METI (2015): Top Runner Program. Developing the World's Best Energy-Efficient Appliance and More. Edited by Ministry of Economy, Trade and Industry, Agency for Natural Resources and Energy, Energy Efficiency and Conservation Division. Tokyo, Japan.

Michaelis, Peter (1996): Ein ökonomischer Orientierungsrahmen für die Umweltpolitik. Kiel: Inst. für Weltwirtschaft (Kieler Diskussionsbeiträge, 270/271).

Miller, Bruce G. (2011): Clean coal engineering technology. Burlington, MA: Butterworth-Heinemann.

Ministry of Environment ROK (2012): Supply of low NOx burner reduces both air pollution and fuel cost. Available online at http://eng.me.go.kr/eng/web/board/read.do?menuId=456&boardMasterId=522&boardId=685&boardCategoryId=, checked on 11/9/2018.

Möller, Detlev (2003): Luft. Chemie, Physik, Biologie, Reinhaltung, Recht. Berlin, New York: W. de Gruyter.

Mooren, C.; Müller, H.; Muhr, M. (1991): Umweltorientierte Fördermaßnahmen des Staates in betrieblichen Investitionskalkülen. In *Zeitschrift für angewandte Umweltforschung* 4 (3), pp. 267–282.

Mostafa, F.; Dillon, T. (2008): A neural network approach to option pricing. In M. Costantino (Ed.): Computational finance and its applications III. [papers presented at the Conference Computational Finance 2008, held in Cádiz in Spain]. COMPUTATIONAL FINANCE 2008. Cadiz, Spain, 27-29 May 2008. International Conference on Computational Finance and Its Applications. Southampton: WIT Press (WIT transactions on information and communication technologies, 41), pp. 71–85.

Mostafa, Fahed; Dillon, Tharam; Chang, Elizabeth (2017): Option Pricing. In Fahed Mostafa, Tharam Dillon, Elizabeth Chang (Eds.): Computational Intelligence Applications to Option Pricing, Volatility Forecasting and Value at Risk. Cham: Springer International Publishing (Studies in Computational Intelligence, 697), pp. 113–135.

Moulton, Brad (2015): Applying SCR NOx reduction in high-dust environments. In *Power Engineering International* 23 (12). Available online at https://www.powerengineeringint.com/articles/print/volume-23/issue-12/features/applying-scr-nox-reduction-in-high-dust-environments.html, checked on 8/29/2018.

Muche, Thomas (2007): Investitionsbewertung in der Elektrizitätswirtschaft mit dem Realoptionsansatz. In *Zeitschrift für Energiewirtschaft* 31 (2), pp. 137–153.

Myers, Stewart C. (1977): Determinants of corporate borrowing. In *Journal of Financial Economics* 5 (2), pp. 147–175. DOI: 10.1016/0304-405X(77)90015-0.

Nalbandian, Herminé (2006): Economics of retrofit air pollution control technologies. London: IEA Clean Coal Centre (CCC (Series) (IEA Coal Research), 111).

Nalbandian-Sugden, Herminé (2016): Operating ratio and cost of coal power generation. London: IEA Clean Coal Centre.

Naturvårdsverket (2006): The Swedish charge on nitrogen oxides. Cost-effective emission reduction. Stockholm: Swedish Environmental Protection Agency (Information facts).

OECD (1993): Advanced emission controls for power plants. Organisation for Economic Co-operation and Development (OECD). Paris.

OECD (2013): Effective carbon prices. Paris: OECD Publishing.

OECD (2018a): OECD.Stat. Available online at https://stats.oecd.org/Index.aspx?DataSetCode=AIR_EMISSIONS#, checked on 10/30/2018.

OECD (2018b): PINE database. Database on Policy Instruments for the Environment. Available online at https://pinedatabase.oecd.org/, checked on 6/15/2018.

Olsen, Brian Kjærgaard; Kügler, Frauke; Castellina, Francesco; Schill, Leonhard; Fehrmann, Rasmus; Jensen, Anker Degn (2017): Deactivation of SCR catalysts by potassium: A study of potential alkali barrier materials. In *VGB PowerTech* (3).

Park, Hojeong (2012): Real option analysis for effects of emission permit banking on investment under abatement cost uncertainty. In *Economic Modelling* 29 (4), pp. 1314–1321. DOI: 10.1016/j.econmod.2012.04.012.

Perridon, Louis; Steiner, Manfred; Rathgeber, Andreas W. (2017): Finanzwirtschaft der Unternehmung. 17th ed. München: Verlag Franz Vahlen.

Peters, Linda (2016): Real Options Illustrated. 1st ed. Cham: Springer.

Peters, Max S.; Timmerhaus, Klaus D.; West, Ronald E. (2003): Plant design and economics for chemical engineers. 5th ed. New York: McGraw-Hill (McGraw-Hill chemical engineering series).

Petters, Arlie O.; Dong, Xiaoying (2016): An Introduction to Mathematical Finance with Applications. Understanding and Building Financial Intuition. New York, NY: Springer New York; Imprint: Springer (Springer Undergraduate Texts in Mathematics and Technology).

Pindyck, Robert S. (2002): Optimal timing problems in environmental economics. In *Journal of Economic Dynamics and Control* 26 (9-10), pp. 1677–1697.

Pratt, John W.; Zeckhauser, Richard J. (1985): Principals and agents. The structure of business. Boston, Mass.

Pritsch, Gunnar; Weber, Jürgen (2001): Die Bedeutung des Realoptionsansatzes aus Controlling-Sicht. In Ulrich Hommel, Martin Scholich (Eds.): Realoptionen in der Unternehmenspraxis. Wert schaffen durch Flexibilität. Berlin [u.a.]: Springer, pp. 13–43.

Project Management Institute (2008): A guide to the project management body of knowledge (PMBOK Guide). 4th ed. Newtown Square: Project Management Institute.

Reedman, Luke; Graham, Paul; Coombes, Peter (2006): Using a Real-Options Approach to Model Technology Adoption Under Carbon Price Uncertainty: An Application to the Australian Electricity Generation Sector. In *Economic Record* 82 (1), pp. S64-S73.

Reis, Stefan (2010): Costs of air pollution control. Analyses of emission control options for ozone abatement strategies. Berlin, Heidelberg: Springer.

Rentz, O.; Nunge, S.; Laforsch, M.; Holtmann, T. (1999): Technical Background Documents for the Actualisation and Assessment of UN/ECE Protocols related to the Abatement of the Transboundary Transport of Volatile Organic Compounds and Nitrogen Oxides from Stationary Sources: French-German Institute for Environmental Research, University of Karlsruhe.

Rentz, Otto (1979): Techno-Ökonomie betrieblicher Emissionsminderungsmassnahmen. Berlin: E. Schmidt (Technological economics, Bd. 4).

Richers, Ulf; Günther, Vivien (2014): Erweiterte Überlegungen zur integrativen Vermeidung von Umweltauswirkungen am Beispiel der Stickoxidemissionen aus Abfallverbrennungsanlagen. Karlsruhe Institute of Technology. Karlsruhe (KIT Scientific Reports, 7680).

Rieger, Marc Oliver (2016): Optionen, Derivate und strukturierte Produkte. 2nd ed. Stuttgart: Schäffer-Poeschel.

Rimmelspacher, J. (1986): DENOX-Anlagen hinter Dampferzeugern. In *VGB Kraftwerkstechnik* 66 (7), pp. 630–631.

Ritzenhofen, Ingmar; Spinler, Stefan (2016): Optimal design of feed-in-tariffs to stimulate renewable energy investments under regulatory uncertainty — A real options analysis. In *Energy Economics* 53, pp. 76–89. DOI: 10.1016/j.eneco.2014.12.008.

Robertson, Sjoerd (2016): How many stones to kill a bird? A Case Study of Policy Interactions within the Netherlands NOx Emission Trading Scheme. Master thesis. Utrecht University, Utrecht. Energy Research Centre of the Netherlands (ECN). Available online at https://dspace.library.uu.nl/handle/1874/337186, checked on 11/9/2018.

Röhrich, Martina (2014): Fundamentals of investment appraisal. An illustration based on a case study. 2nd ed. Berlin, Boston: De Gruyter Oldenbourg.

Rosenberg, H. S.; Oxley, J. H. (1993): Selective Catalytic Reduction for NOx Control at Coal-fired Power Plants. ICAC Forum '93, Controlling Air Toxics and NOx Emissions. Baltimore, 1993.

Ross, Sheldon M. (2011): An elementary introduction to mathematical finance. Third edition. New York: Cambridge University Press.

Ruhrberg, Martin (2016): Implementation of BAT in the German Electricity Sector. Workshop to promote the understanding and implementation of BAT across the entire UNECE region with focus on countries in the EECCA region. Berlin, 2016. Available online at https://www.unece.org/fileadmin/DAM/env/lrtap/capacity_building/BAT_Workshop_2016/14_BAT_Implementation_Power_Sector_-_Ruhrberg.pdf, checked on 10/30/2018.

Sarkis, Joseph; Tamarkin, Maurry (2005): Real Options Analysis for "Green Trading": The Case of Greenhouse Gases. In *The Engineering Economist* 50 (3), pp. 273–294. DOI: 10.1080/00137910500227208.

Scarbrough, Tim; Kuenen, Jeroen; Dellaert, Stijn; Smekens, Koen; Lodewijks, Pieter; Dams, Yoko; Sykes, James (2017): Technical support for developing the profile of certain categories of Large Combustion Plants regulated under the Industrial Emissions Directive. London. Available online at https://circabc.europa.eu/sd/a/f568a5b1-8c7a-475c-8162-a6c47b86ef7f/LCP%20profile.pdf, checked on 10/30/2018.

Schäfer, Henry (2005): Unternehmensinvestitionen. Grundzüge in Theorie und Management ; mit 98 Tabellen. 2nd ed. Heidelberg: Physica-Verlag Heidelberg (Physica-Lehrbuch).

Schaltegger, Stefan; Sturm, Andreas J. (1994): Ökologieorientierte Entscheidungen in Unternehmen. Ökologisches Rechnungswesen statt Ökobilanzierung ; Notwendigkeit, Kriterien, Konzepte. 2nd ed. Bern [u.a.]: Haupt (Schriftenreihe des Instituts für Betriebswirtschaft, Wirtschaftswissenschaftliches Zentrum der Universität Basel, 27).

Schätter, Frank (2016): Decision support system for a reactive management of disaster-caused supply chain disturbances. Karlsruhe: KIT Scientific Publishing (Produktion und Energie, Band 14).

Schiel, Carmen; Glöser-Chahoud, Simon; Schultmann, Frank (2019): A real option application for emission control measures. In *J Bus Econ* 89 (3), pp. 291–325. DOI: 10.1007/s11573-018-0913-9.

Schneider, Dieter (1992): Investition, Finanzierung und Besteuerung. 7th ed. Wiesbaden: Gabler Verlag.

Schnelle, Karl B.; Ternes, Mary Ellen; Dunn, Russell (2016): Air pollution control technology handbook. 2nd ed. Boca Raton: Taylor & Francis.

Schnitkey, Gary (2016): Anhydrous Ammonia, Corn, and Natural Gas Prices Over Time. In *farmdoc daily* 6 (112).

Schreifels, Jeremy J.; Wang, Shuxiao; Hao, Jiming (2012): Design and operational considerations for selective catalytic reduction technologies at coal-fired boilers. In *Front. Energy* 6 (1), pp. 98–105. DOI: 10.1007/s11708-012-0171-4.

Schröder, A.; Willeke, M. (1995): Prozeßorientierte Investitionsrechnung zur Bewertung von Umweltschutzprojekten. In *Controlling* (3), pp. 132–138.

Schroeder, H. C. (2017): The implications of one-mill operation for the operating regime and control of a coal plant. In *Power Engineering International* 25 (5).

Schulte Beerbühl, Simon; Hiete, Michael (2012): Emerging Techniques and Technologies for Large Combustion Plants up to 500 MWth Capacity. EMTECH50-500 Subgroup Final Report. Edited by ADEME. Angers.

Schultes, Michael (1996): Abgasreinigung. Verfahrensprinzipien, Berechnungsgrundlagen, Verfahrensvergleich. Berlin: Springer.

Schultmann, Frank; Jochum, Rainer; Rentz, Otto (2001): A methodological approach for the economic assessment of best available techniques demonstrated for a case study from the steel industry. In *The International Journal of Life Cycle Assessment* 6 (1), pp. 19–27. DOI: 10.1007/BF02977591.

Sekar, R. C. (2005): Carbon Dioxide Capture from Coal-Fired Power Plants: A Real Options Analysis. Massachusetts Institute of Technology (LFEE 2005-002 RP). Available online at http://sequestration.mit.edu/pdf/LFEE_2005-002_RP.pdf, checked on 11/9/2018.

Senge, Robin; Bösner, Stefan; Dembczyński, Krzysztof; Haasenritter, Jörg; Hirsch, Oliver; Donner-Banzhoff, Norbert; Hüllermeier, Eyke (2014): Reliable classification. Learning classifiers that distinguish aleatoric and epistemic uncertainty. In *Information Sciences* 255, pp. 16–29. DOI: 10.1016/j.ins.2013.07.030.

Simon, Herbert A. (1977): The new science of management decision. Rev. ed. Englewood Cliffs, N.J.: Prentice-Hall.

Singh, Anita; Agrawal, Madhoolika (2008): Acid rain and its ecological consequences. In *Journal of Environmental Biology* 29 (1), pp. 15–24.

Sinha, A. K. (2016): Meeting new environment norms - challenges and possibilities. EEC Power India. New Delhi, India, 2016. Available online at http://eecpowerindia.com/codelibrary/ckeditor/ckfinder/userfiles/files/NTPC.pdf, checked on 11/9/2018.

Sloss, L. L. (2016): Levelling the intermittency of renewables with coal. IEA Clean Coal Centre. London.

Sloss, L. L. (2017): Emerging markets for pollution control retrofits. IEA Clean Coal Centre. London.

Smekens, Koen (2013): Biomass co-firing in coal power plants in the Netherlands: effects on performance and air pollutant emissions. Edited by ECN Policy Studies. ECN. Petten. Available online at https://www.ecn.nl/publications/PdfFetch.aspx?nr=ECN-N--13-030, updated on 11/9/2018.

Smit, Han T. J.; Trigeorgis, Lenos (2012): Strategic investment. Real options and games. Princeton (N.J.), Oxford (Royaume Uni): Princeton University Press.

South Coast AQMD (2018): REgional CLean Air Incentives Market (RECLAIM). Edited by South Coast Air Quality Management District. Available online at http://www.aqmd.gov/home/programs/business/about-reclaim, checked on 11/9/2018.

Spengler, Thomas (1998): Industrielles Stoffstrommanagement. Betriebswirtschaftliche Planung und Steuerung von Stoff- und Energieströmen in Produktionsunternehmen. Berlin: E. Schmidt (Technological economics, Bd. 54).

Stavins, Robert N. (2003): Experience with Market-Based Environmental Policy Instruments. In Karl-Göran Mäler (Ed.): Handbook of environmental economics, vol. 1. Amsterdam [u.a.]: North-Holland (Handbooks in economics, 20), pp. 355–435.

Stentoft, Lars (2004): Assessing the Least Squares Monte-Carlo Approach to American Option Valuation. In *Review of Derivatives Research* 7 (2), pp. 129–168. DOI: 10.1023/B:REDR.0000031176.24759.e6.

Strauss, Karl (2016): Kraftwerkstechnik. Zur Nutzung fossiler, nuklearer und regenerativer Energiequellen. 7. Aufl. 2016. Berlin, Heidelberg: Springer Berlin Heidelberg; Imprint: Springer Vieweg (VDI-Buch).

Styczynski, Zbigniew A.; Stötzer, Martin; Lombardi, Pio Alessandro (2014): Primärenergien. In K.-H Grote, J. Feldhusen (Eds.): Dubbel. Taschenbuch für den Maschinenbau. 24. aktualisierte und erweiterte Auflage. Berlin: Springer Berlin, pp. 783–795.

Surminski, Swenja (2015): The role of insurance risk transfer in encouraging climate investment in developing countries. In Pierre-Marie Dupuy, Jorge E. Vinuaels (Eds.): Harnessing foreign investment to promote environmental protection. Incentives and Safeguards. Cambridge: Cambridge Univ Press, pp. 228–253.

Szolgayova, Jana; Fuss, Sabine; Obersteiner, Michael (2008): Assessing the effects of CO2 price caps on electricity investments—A real options analysis. In *Energy Policy* 36 (10), pp. 3974–3981. DOI: 10.1016/j.enpol.2008.07.006.

Tarui, Nori; Polasky, Stephen (2005): Environmental regulation with technology adoption, learning and strategic behavior. In *Journal of Environmental Economics and Management* 50 (3), pp. 447–467. DOI: 10.1016/j.jeem.2005.01.004.

Taudes, Alfred; Natter, Martin; Trcka, Michael (1998): Real Option Valuation with Neuronal Networks. In *International Journal of Intelligent Systems in Accounting, Finance & Management* 7 (1), pp. 43–52.

TFTEI (2015a): Estimation of Costs of Reduction Techniques for LCP. Methodology. TFTEI Technical Secretariat. Available online at http://tftei.citepa.org/images/files/2015-02-16/TFTEI_cost_calculation_methodology.pdf, checked on 11/9/2018.

TFTEI (2015b): Mandate of TFTEI. Available online at http://tftei.citepa.org/, checked on 11/9/2018.

Thøgersen, Joakim Reimer; Jensen-Holm, Hans (2010): SCR DENOX Trends 2009. In *VGB PowerTech* (4), pp. 35–42.

Tomei, G. L. (Ed.) (2015): Steam. Its generation and use. 42nd ed. Barberton, Ohio: Babcock & Wilcox Company.

Trigeorgis, Lenos (1996): Real options. Managerial flexibility and strategy in resource allocation. Cambridge: MIT Press.

Trigeorgis, Lenos; Reuer, Jeffrey J. (2017): Real options theory in strategic management. In *Strategic Management Journal* 38 (1), pp. 42–63. DOI: 10.1002/smj.2593.

Tsitsiriki, M.; Bereketidou, O.; Latsios H.; Goula M.A. (2007): System design and cost estimation for NOx selective catalytic reduction (SCR) on coal-fired boilers. Kos Island, Greece (Proceedings of the 10th International Conference on Environmental Science and Technology).

Umweltbundesamt (2012): Methodenkonvention 2.0 zur Schätzung von Umweltkosten. Ökonomische Bewertung von Umweltschäden. Dessau-Roßlau.

Umweltbundesamt (2018): Kohlendioxid-Emissionsfaktoren für die deutsche Berichterstattung atmosphärischer Emissionen. Carbon Dioxide Emissions for the German Atmospheric Emission Reporting 1990 – 2016. Edited by Umweltbundesamt. Dessau. Available online at https://www.umweltbundesamt.de/sites/default/files/medien/361/dokumente/co2_ef_2018_komplett.xlsx, checked on 11/9/2018.

UNECE (1988): The 1988 Sofia Protocol concerning the Control of Emissions of Nitrogen Oxides or their Transboundary Fluxes. Edited by Executive Body for the Convention on Long-range Transboundary Air Pollution. Available online at https://www.unece.org/fileadmin/DAM/env/lrtap/full%20text/1988.NOX.e.pdf, checked on 11/1/2018.

UNECE (2013): 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone to the Convention on Long- range Transboundary Air Pollution, as amended on 4 May 2012. Edited by Executive Body for the Convention on Long-range Transboundary Air Pollution.

UNECE (2015a): Guidance document on control techniques for emissions of sulphur, nitrogen oxides, volatile organic compounds and particulate matter (including PM10, PM2.5 and black carbon) from stationary sources. Edited by Executive Body for the Convention on Long-range Transboundary Air Pollution (ECE/EB.AIR/117).

UNECE (2015b): Report of the Executive Body on its thirty-third session. Executive Body for the Convention on Long-range Transboundary Air Pollution. United Nations Economic Commission for Europe.

UNFCCC (2014): United Nations Climate Change website. Edited by United Nations Framework Convention on Climate Change. Available online at http://unfccc.int/2860.php, checked on 11/9/2018.

US EIA (2015): Electric Power Annual 2013. U.S. Energy Information Administration.

US EIA (2018): International Energy Statistics. Independant Statistics & Analysis. U.S. Energy Information Administration. Available online at http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=12, checked on 11/15/2018.

US EPA (1998): NOx. How nitrogen oxides affect the way we live and breathe. Office of Air Quality Planning and Standards (EPA-456/F-98-005).

US EPA (2002): EPA Air Pollution Control Cost Manual. Sixth Edition. Edited by United States Environmental Protection Agency (EPA/452/B-02-001).

US EPA (2005): International Experiences with Economic Incentives for Protecting the Environment. Edited by United States Environmental Protection Agency. National Center for Environmental Economics.

US EPA (2016): EPA Air Pollution Control Cost Manual. Seventh Edition. Edited by United States Environmental Protection Agency.

Uszczapowski, Igor (2008): Optionen und Futures verstehen. Grundlagen und neue Entwicklungen. Orig.-ausg., 6., aktualisierte und erw. Aufl. München, [München]: Dt. Taschenbuch-Verl.; Beck (Dtv, 5808 : Beck-Wirtschaftsberater).

van der Kamp, Jonathan (2017): Social cost-benefit analysis of air pollution control measures. Advancing environmental-economic assessment methods to evaluate industrial point emission sources. Karlsruhe: KIT Scientific Publishing.

van der Slot, Arnoud; Frans, David; Ammermann, Heiko; Goemans, Marijn; Achterberg, Floris (2015): Keep your megaproject on track. Implement decision-making support for successful megaproject management. Edited by Roland Berger GMBH. Available online at https://www.rolandberger.com/en/Publications/Keep-your-megaproject-on-track.html, checked on 11/9/2018.

Vatavuk, William M. (2002): Updating the CE Plant Cost Index. In *Chemical Engineering* (01), 62-70.

VDI (2001): Determination of costs for industrial environmental protection measures. VDI3800. Berlin.

Vijay, Samudra; DeCarolis, Joseph F.; Srivastava, Ravi K. (2010): A bottom-up method to develop pollution abatement cost curves for coal-fired utility boilers. In *Energy Policy* 38 (5), pp. 2255–2261.
DOI: 10.1016/j.enpol.2009.12.013.

Voje, H.-H.; Fischer, B.; Mittelbach, G. (1991): Inbetriebnahme und Betriebserfahreungen mit SNCR-Anlagen an Schmelzfeuerkesseln. In *VGB Kraftwerkstechnik* 71 (10), pp. 945–951.

Vose, David (2015): Do your projects meet their budgets? Vose Software BVBA. Gent. Available online at http://blog.vosesoftware.com/do-your-projects-meet-their-budgets/, checked on 11/9/2018.

Walker, W. E.; Harremoës, P.; Rotmans, J.; van der Sluijs, J. P.; van Asselt, M.B.A.; Janssen, P.; Krayer von Krauss, M. P. (2003): Defining Uncertainty. A Conceptual Basis for Uncertainty Management in Model-Based Decision Support. In *Integrated Assessment* 4 (1), pp. 5–17. DOI: 10.1076/iaij.4.1.5.16466.

Warnatz, Jürgen; Dibble, Robert W.; Maas, Ulrich (2006): Combustion. Physical and Chemical Fundamentals, Modeling and Simulation, Experiments, Pollutant Formation. 4th ed. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg.

Wellburn, Allen (1997): Luftverschmutzung und Klimaänderung. Auswirkungen auf Flora, Fauna und Mensch. Berlin Heidelberg: Springer.

Welling, Andreas; Lukas, Elmar; Kupfer, Stefan (2015): Investment timing under political ambiguity. In *J Bus Econ* 85 (9), pp. 977–1010. DOI: 10.1007/s11573-015-0771-7.

WHO (2018): Ambient (outdoor) air quality and health. Fact sheet N°313. Available online at http://www.who.int/mediacentre/factsheets/fs313/en/, checked on 11/9/2018.

Wiatros-Motyka, Malgorzata; Nalbandian-Sugden, Herminé (2018): NOx control for high ash coals. IEA Clean Coal Centre. London (IEA Report, CCC/285).

Wiesel, A.; Schuster, A.; Maier, H. (2017): Regeneration von SCR-Katalysatoren – Untersuchung verschiedener Einflussfaktoren auf den Nassreinigungsprozess. In *VGB PowerTech* (3), pp. 51–55.

Wolfrum, Jrgen (1972): Bildung von Stickstoffoxiden bei der Verbrennung. In *Chemie Ing. Techn.* 44 (10), pp. 656–659. DOI: 10.1002/cite.330441004.

Wu, Z. (2001): Air pollution control costs for coal-fired power stations. London: Clean Coal Centre, IEA Coal Research (Clean Coal Centre, 53).

Xu, Liying; Sepehrnoori, Kamy; Dyer, James; van Rensburg, Willem C. (2013): Application of Real Options to Valuation and Decision-making in the Petroleum E&P Industry. In : SPE Hydrocarbon Economics and Evaluation Symposium. SPE Hydrocarbon Economics and Evaluation Symposium. Calgary, Alberta, Canada, 2012-09-24: Society of Petroleum Engineers.

Yang, Hang; Zhang, Yongxin; Zheng, Chenghang; Wu, Xuecheng; Chen, Linghong; Gao, Xiang; Fu, Joshua S. (2018): Energy consumption and energy-saving potential analysis of pollutant abatement systems in a 1000-MW coal-fired power plant. In *Journal of the Air & Waste Management Association (1995)* 68 (9), pp. 920–930. DOI: 10.1080/10962247.2018.1454992.

Yang, Ming; Blyth, William (2007): Modeling Investment Risks and Uncertainties with Real Options Approach. International Energy Agency (LTO/2007/WP 01). Available online at https://www.iea.org/publications/freepublications/publication/ROA_Model.pdf, checked on 11/9/2018.

Yang, Yongxin; Zheng, Yu; Hospedales, Timothy M. (2017): Gated Neural Networks for Option Pricing. Rationality by Design. In *Proceedings of the Thirty-First AAAI Conference on Artificial Intelligence (AAAI-17)*, pp. 52–58.

Yelverton, William H. (2009): Coal Utility Environmental Cost (CUECost) Workbook Development Documentation. Version 5.0. Edited by U.S. Environmental Protection Agency (EPA/600/R-09/131).

Zabetta, Edgardo Coda; Hupa, Mikko; Saviharju, Kari (2005): Reducing NOx Emissions Using Fuel Staging, Air Staging, and Selective Noncatalytic Reduction in Synergy. In *Industrial & Engineering Chemistry Research* 44 (13), pp. 4552–4561. DOI: 10.1021/ie050051a.

Zeldovich, Y. B. (1946): The oxidation of nitrogen in combustion and explosions. In *Acta Physicochim* USSR 21 (577).

Zhang, Yue-Jun; Wei, Yi-Ming (2010): An overview of current research on EU ETS: Evidence from its operating mechanism and economic effect. In *Applied Energy* 87 (6), pp. 1804–1814. DOI: 10.1016/j.apenergy.2009.12.019.

Zheng, Yuanjing; Jensen, Anker Degn; Johnsson, Jan Erik (2005): Deactivation of V2O5-WO3-TiO2 SCR catalyst at a biomass-fired combined heat and power plant. In *Applied Catalysis B: Environmental* 60 (3-4), pp. 253–264. DOI: 10.1016/j.apcatb.2005.03.010.

Zhou, Wenji; Zhu, Bing; Fuss, Sabine; Szolgayová, Jana; Obersteiner, Michael; Fei, Weiyang (2010): Uncertainty modeling of CCS investment strategy in China's power sector. In *Applied Energy* 87 (7), pp. 2392–2400. DOI: 10.1016/j.apenergy.2010.01.013.

Zhu, Lei; Fan, Ying (2011): A real options–based CCS investment evaluation model: Case study of China's power generation sector. In *Applied Energy* 88 (12), pp. 4320–4333. DOI: 10.1016/j.apenergy.2011.04.005.

Zimmer, Konrad (2016): Entscheidungsunterstützung zur Auswahl und Steuerung von Lieferanten und Lieferketten unter Berücksichtigung von Nachhaltigkeitsaspekten. Karlsruhe, Baden: KIT Scientific Publishing (Produktion und Energie, 17).

Zsidisin, George A.; Ritchie, Bob (2008): Supply chain risk. A handbook of assessment, management, and performance. New York: Springer (International series in operations research & management science, 124).

PRODUKTION UND ENERGIE

Karlsruher Institut für Technologie (KIT)
Institut für Industriebetriebslehre und Industrielle Produktion
Deutsch-Französisches Institut für Umweltforschung

ISSN 2194-2404

Band 1 **National Integrated Assessment Modelling zur Bewertung umweltpolitischer Instrumente.**
Entwicklung des otello-Modellsystems und dessen Anwendung auf die Bundesrepublik Deutschland. 2012
ISBN 978-3-86644-853-7

Band 2 **Erhöhung der Energie- und Ressourceneffizienz und Reduzierung der Treibhausgasemissionen in der Eisen-, Stahl- und Zinkindustrie (ERESTRE).** 2013
ISBN 978-3-86644-857-5

Band 3 Frederik Trippe
Techno-ökonomische Bewertung alternativer Verfahrenskonfigurationen zur Herstellung von Biomass-to-Liquid (BtL) Kraftstoffen und Chemikalien. 2013
ISBN 978-3-7315-0031-5

Band 4 Dogan Keles
Uncertainties in energy markets and their consideration in energy storage evaluation. 2013
ISBN 978-3-7315-0046-9

Band 5 Heidi Ursula Heinrichs
Analyse der langfristigen Auswirkungen von Elektromobilität auf das deutsche Energiesystem im europäisschen Energieverbund. 2013
ISBN 978-3-7315-0131-2

Band 6 Julian Stengel
Akteursbasierte Simulation der energetischen Modernisierung des Wohngebäudebestands in Deutschland. 2014
ISBN 978-3-7315-0236-4

Band 7 Sonja Babrowski
Bedarf und Verteilung elektrischer Tagesspeicher im zukünftigen deutschen Energiesystem. 2015
ISBN 978-3-7315-0306-4

Band 8 Marius Wunder
Integration neuer Technologien der Bitumenkalthandhabung in die Versorgungskette. 2015
ISBN 978-3-7315-0319-4

Band 9 Felix Teufel
Speicherbedarf und dessen Auswirkungen auf die Energiewirtschaft bei Umsetzung der politischen Ziele zur Energiewende. 2015
ISBN 978-3-7315-0341-5

Band 10 D. Keles, L. Renz, A. Bublitz, F. Zimmermann, M. Genoese, W. Fichtner, H. Höfling, F. Sensfuß, J. Winkler
Zukunftsfähige Designoptionen für den deutschen Strommarkt: Ein Vergleich des Energy-only-Marktes mit Kapazitätsmärkten. 2016
ISBN 978-3-7315-0453-5

Band 11 Patrick Breun
Ein Ansatz zur Bewertung klimapolitischer Instrumente am Beispiel der Metallerzeugung und -verarbeitung. 2016
ISBN 978-3-7315-0494-8

Band 12 P. Ringler, H. Schermeyer, M. Ruppert, M. Hayn, V. Bertsch, D. Keles, W. Fichtner
Decentralized Energy Systems, Market Integration, Optimization. 2016
ISBN 978-3-7315-0505-1

Band 13 Marian Hayn
Modellgestützte Analyse neuer Stromtarife für Haushalte unter Berücksichtigung bedarfsorientierter Versorgungssicherheitsniveaus. 2016
ISBN 978-3-7315-0499-3

Band 14 Frank Schätter
Decision support system for a reactive management of disaster-caused supply chain disturbances. 2016
ISBN 978-3-7315-0530-3

Band 15 Robert Kunze
Techno-ökonomische Planung energetischer Wohngebäudemodernisierungen: Ein gemischt-ganzzahliges lineares Optimierungsmodell auf Basis einer vollständigen Finanzplanung. 2016
ISBN 978-3-7315-0531-0

Band 16 A. Kühlen, J. Stengel, R. Volk, F. Schultmann, M. Reinhardt, H. Schlick, S. Haghsheno, A. Mettke, S. Asmus, S. Schmidt, J. Harzheim
ISA: Immissionsschutz beim Abbruch - Minimierung von Umweltbelastungen (Lärm, Staub, Erschütterungen) beim Abbruch von Hoch-/Tiefbauten und Schaffung hochwertiger Recyclingmöglichkeiten für Materialien aus Gebäudeabbruch. 2018
ISBN 978-3-7315-0534-1

Band 17 Konrad Zimmer
Entscheidungsunterstützung zur Auswahl und Steuerung von Lieferanten und Lieferketten unter Berücksichtigung von Nachhaltigkeitsaspekten. 2016
ISBN 978-3-7315-0537-2

Band 18 Kira Schumacher, Wolf Fichtner and Frank Schultmann (Eds.)
Innovations for sustainable biomass utilisation in the Upper Rhine Region. 2017
ISBN 978-3-7315-0423-8

Band 19 Sophia Radloff
Modellgestützte Bewertung der Nutzung von Biokohle als Bodenzusatz in der Landwirtschaft. 2017
ISBN 978-3-7315-0559-4

Band 20 Rebekka Volk
Proactive-reactive, robust scheduling and capacity planning of deconstruction projects under uncertainty. 2017
ISBN 978-3-7315-0592-1

Band 21 Erik Merkel
Analyse und Bewertung des Elektrizitätssystems und des Wärmesystems der Wohngebäude in Deutschland. 2017
ISBN 978-3-7315-0636-2

Band 22 Rebekka Volk (Hrsg.)
Entwicklung eines mobilen Systems zur Erfassung und Erschließung von Ressourceneffizienzpotenzialen beim Rückbau von Infrastruktur und Produkten („ResourceApp"): Schlussbericht des Forschungsvorhabens. 2017
ISBN 978-3-7315-0653-9

Band 23 Thomas Kaschub
Batteriespeicher in Haushalten unter Berücksichtigung von Photovoltaik, Elektrofahrzeugen und Nachfragesteuerung. 2017
ISBN 978-3-7315-0688-1

Band 24 Felix Hübner, Rebekka Volk, Oktay Secer, Daniel Kühn, Peter Sahre, Reinhard Knappik, Frank Schultmann, Sascha Gentes, Petra von Both
Modellentwicklung eines ganzheitlichen Projektmanagementsystems für kerntechnische Rückbauprojekte (MogaMaR): Schlussbericht des Forschungsvorhabens. 2018
ISBN 978-3-7315-0762-8

Band 25 Karoline Fath
Technical and economic potential for photovoltaic systems on buildings. 2018
ISBN 978-3-7315-0787-1

Band 26 Ann-Kathrin Müller
Decision Support for Biomass Value Chains for the Production of Biochemicals Considering Uncertainties. 2018
ISBN 978-3-7315-0820-5

Band 27 Jonatan J. Gómez Vilchez
The Impact of Electric Cars on Oil Demand and Greenhouse Gas Emissions in Key Markets. 2019
ISBN 978-3-7315-0914-1

Band 28 Carmen Schiel
Real Option Based Appraisal of Environmental Investments – An Assessment of NO_x Emission Control Techniques in Large Combustion Plants. 2019
ISBN 978-3-7315-0925-7

INSTITUT FÜR INDUSTRIEBETRIEBSLEHRE UND INDUSTRIELLE PRODUKTION

DEUTSCH-FRANZÖSISCHES INSTITUT FÜR UMWELTFORSCHUNG

Conventional industrial investments aim at gaining profit for a company by providing assets and resources that enable successful business operation. Environmental investments, such as NO_X emission control measures in large combustion plants, however, hardly gain profit but are enforced by policy. Such complex and costly investments can generally be expected to be delayed as much as legally feasible. Nevertheless, if increasing expenditures for the same investment in the future are likely to occur, an advanced investment may be favorable. In this case, future flexibility is lost, yet the risk that results from uncertain future developments is reduced or avoided. This decision situation is reflected in the book via a two-stage modelling approach. A cost calculation methodology for NO_X control techniques in large combustion plants is presented, complemented by a real option based decision support model for investments that do not gain economic profit. The results of the case studies investigated in the political context of the EU and India reveal a general need for disruptive settings to cause an advanced investment. Such settings can be generated by environmental policy instruments or by market developments. Yet, the impact and the resulting levers of different measures and settings differ significantly and are a major aspect of the policy assessment in this work.

ISSN 2194-2404
ISBN 978-3-7315-0925-7

ISBN 978-3-7315-0925-7
9 783731 509257 >

Gedruckt auf FSC-zertifiziertem Papier