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Flexible Operating Mechanisms

**Improving the Business Case for Pulverized Coal Power Plants
with Post Combustion Capture**

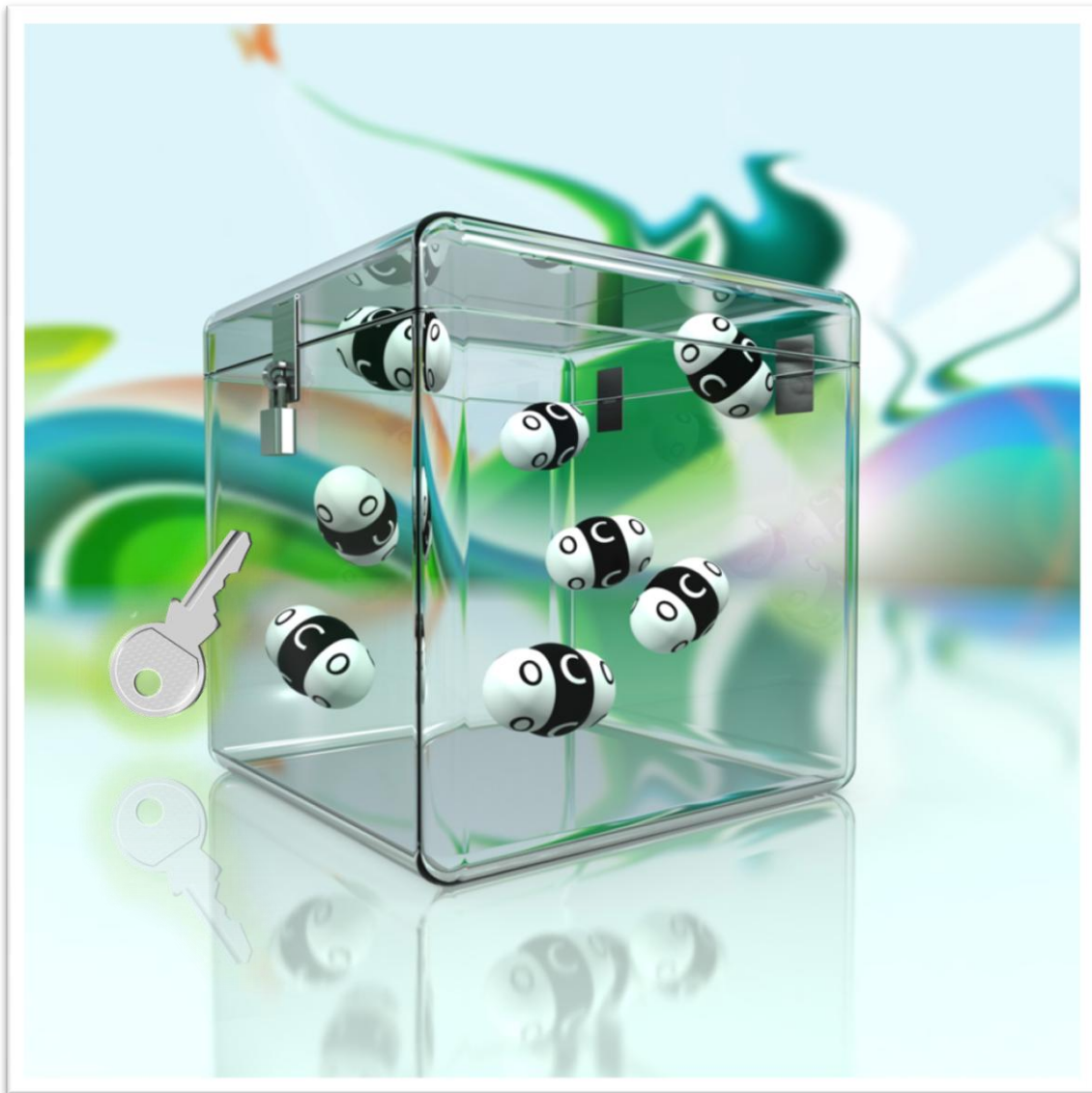Prepared by: Marinus Verbaan (TU-Delft)

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TUDelft
Delft University of Technology

TNO innovation for life

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**Improving the Business Case for Pulverized Coal Power Plants
with Post Combustion Capture**

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Graduation Date: August 22nd, 2011

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Executive Summary

Employing Flexible Operating Mechanisms (FOMs) for coal power plants with post combustion capture will <u>improve</u> the business case and provide plant operators with more flexibility to counteract changes in the market and demand. In conjunction with TNO Separation Technology a model (chapter 3) was developed to evaluate different FOMs on their ability to improve performance in relation to a reference plant. The FOMs model is adaptable and can therefore be altered to fit a certain operational environment.

The operational environment for coal plants are changing; CO_2 markets are maturing, growing fraction of sustainable and renewable sources in the energy mix, public concerns about emissions and global warming intensify and fuel prices are becoming less predictable. Moreover, if coal plants want to remain operational throughout its lifetime, it is expected that coal plants will have to invest in capture technologies. Within this dynamic arena, coal plants will have to operate; however, coal plants are 'inflexible' to quick changes of demand and market signals. FOMs will aid coal plants to increase their flexibility and degrees of freedom by manipulating the operation of a capture plant.

Post combustion capture offers, in contrast to other capture approaches, the ability to be retrofitted to existing plants within reasonable timeframes and at lowest costs. Globally, coal power plants generate more than 60% of the power and heat demand. Hence, policy developers have suggested that coal power plants be the first to implement these mitigation technologies. To incentivize the coal plant owners, the European Union, has deemed it necessary, starting in 2013, that all energy producers will have to buy their CO_2 emission rights (CERs) from a full auctioning market.

Flexible Operating Mechanisms are a means for a coal plant with capture to change its operational status to strategically take advantage of high electricity prices and/or low CO_2 prices. Three FOMs have been developed and each has a different quality; i) switching the capture plant on or off, ii) intermediate storage of CO_2 rich solvent during the peak prices to regain the energy penalty of continued capture processes and iii) partial capture – technically not a FOM but analyzed as such.

The thesis poses the main question:

How can Flexible Operating Mechanisms (FOMs) improve the business case of an Advanced Super Critical (ASC) pulverized coal power plant with post combustion capture?

Capture ONorOFF can turn the capture plant off when electricity prices are high enough to cover the costs of the emitted CO_2. Is the expected profit greater than the expenses of emitting CO_2 to the atmosphere this action is warranted. Another FOM, intermediate storage will stop stripping and compression when prices are high and store the additional invested solvent. When prices fall the stripping and compression will recommence at a lower cost. The net result is that intermediate storage adds value to any post combustion capture plant. The last FOM is the installation of a smaller capacity capture plant in relation to the coal fired power plant. As expected smaller plants perform better at lower CO_2 prices and are operational faster and more frequent than larger capture plants employing the ONorOFF FOM. The <u>advice</u>, to coal plant operators / owner is to invest in a small capture plant, and possibly intermediate storage, if enough space is available.

The conclusion of this thesis can be summarized as such; FOMs improve the economic business case and also present coal power plants with additional flexibility. This added flexibility could allow coal plants to provide auxiliary services to the grid. However, the CO_2 and electricity prices will decide whether or not a capture plant is built. When the environment is favorable, an initial investment in a smaller capacity of capture (e.g. 40%), whilst employing the ONorOFF flexible operating mechanism is preferable under most conditions. Should prices of CO_2 rise faster than predicted an additional 40/60% plant could be added. The benefit of the FOMs is that they create value at lower CO_2 prices than a reference plant with capture. Another, conclusion that can be drawn, in response to the main research question, is the fact that intermediate storage provides an additional revenue stream should other factors, such as regulation and integration with the CCS value chain, limit the use of switching between full and zero load (ONorOFF).

The two recommendations that warrant quick attention are; i) the combination of partial scale capture (ONorOFF) and intermediate storage. Do these two FOMs conflict or can they function / operate at the same plant and ii) development of a model that can implement electricity and CO_2 trends.

Preface

This thesis is written as the final requirement to graduate with a Master's of Science in Systems Engineering, Policy Analysis and Management from the Delft University of Technology. The thesis research question was in part posed by TNO separation Technology and CATO2. Although the direction of the research was left to the author, the general aim was to <u>examine the economic benefit of flexible operation of post combustion capture plants</u>.

From the initial literature research and subsequent thesis proposal several flexible operations of a post combustion capture plant were identified; named Flexible Operating Mechanisms (FOMs). From this desktop research it was found that the fluctuations and variations in the CO_2 and electricity prices could benefit some of these operations. These operations were studied in greater detail and are presented in this report. The focus, proposed by TNO, was on the techno-economic performance of these flexible operations. Also, the question was raised to increase realism in the business case; in order to achieve this actual electricity prices and the coal plants load profile were included. However, being a technical policy and management student the inclusion of institutional and policy effects should be included. This is one of the major changes that have been integrated into this report following the green light version of this report; the record of changes in respect to the green light version has been included in appendix D. Although, the main body of knowledge in the report focus on techno-economic issues; chapter 6 (conclusions and recommendations), section 6.6, discusses the impact of institutional and governance aspects on the functionality of the FOMs.

An academic/scientific article has also been included in this report and can be found in Appendix C. The article has a deeper focus on the institutional and governance issues in comparison to the main report. The aim of the article is to demonstrate that these FOMs do improve the business case; i.e. in a brief but concise summary of the report, and then discusses which obstacles the implementation of these FOMs, in the "real" world, could face. Hence, the article builds upon the recommendations of the initial report.

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Marinus Verbaan – Delft – August 2011

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List of Abbreviations

APX:	Amsterdam Power Exchange
ASC:	Advanced Super Critical (pulverized coal power plant)
Avg:	Average
BMU:	German Federal Ministry for the Environment
CAPEX:	Capital Expenses
CBR:	Cost Benefit Ratio
CCS:	Carbon Capture and Storage
CER:	Carbon Emission Rights
CO_2:	Carbon dioxide
COA:	Cost of CO_2 Avoided (€/ton CO_2)
COE:	Cost of Electricity (€/MWh)
ELD:	Environmental Liabilities Directive
EPS:	Emission Performance Standard
EU ETS:	European Union Emission Trading Scheme
FOMs:	Flexible Operating Mechanisms
GHG:	Greenhouse Gasses
GJ:	Gigajoule
IEA:	International Energy Agency
IED:	Industrial Emission Directive
IPCC:	International Panel on Climate Change
IPPC:	Integrated Pollution Prevention Directive
LCPD:	Large Combustion Plant Directive
M€:	Million Euro
MEA:	Mono-ethanolamine
MWh:	Megawatt per hour
NAP:	National Allocation Plan
NO_x:	Nitrous Oxides
NPV:	Net Present Value
NUMBY:	Not under my back yard
OPEX:	Operational Expenses
PCC:	Post Combustion Capture
SO_2:	Sulphur Dioxide
TCI:	Total Capital Investment
TNO:	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands organization for applied scientific research)
TPC:	Total Plant Capital
TUDelft:	Delft University of Technology
V&V:	Verification and Validation
WRI:	World Resource Institute

Chapter 1 *Introduction*

This chapter clarifies the aim of this thesis. In section 1.1, it will introduce the importance of CCS to climate change mitigation. Section 1.2, shows that coal-fired power plants are expected to adopt post combustion capture as a means to reduce their CO_2 emissions. Due to the high associated costs with capture an improvement of the current business case is desired; in section 1.3, flexibility is argued to be key in achieving this cost reduction. In section 1.4, the main research question is formulated and its underlying sub-questions are defined.

1.1 Importance of Carbon Capture & Storage for Climate Change Mitigation

Anthropogenic emissions of greenhouse gases (GHG) such as Carbon dioxide (CO_2) to the atmosphere are expected to cause significant global climate change (IPPC, 2001). The most noteworthy anthropogenic greenhouse gas is CO_2. CO_2 is primarily produced by the combustion of fossil fuels. Presently, more than 80% of global energy needs are provided by fossil fuels (IEA, 2003). In order to reduce these emissions to the atmosphere several global initiatives have been or are being committed too; starting with the Kyoto protocol in 1997 and recently attempts were made in Copenhagen 2009, Denmark and Cancun 2010, Mexico. However, reaching a consensus has been problematic at best. Measures, such as increasing renewable fuel sources or improving efficiencies, will reduce emissions but a rapid shift from fossil fuels could cause severe disruption to global economic growth (Davison, 2006). A possible technique that could bridge the current fossil fuel based economy with a carbon-emission-free economy is Carbon Capture and Storage (CCS) (Linden, 1999).

Experts in the fields of climate and energy agree that CCS is a valuable asset to reduce CO_2 emissions. Furthermore CCS features prominently in almost every blueprint to limit CO_2 emissions until 2050 (IEA, 2008a; IPPC 2007). CCS is not only supported by the scientific community, it has also received vast interest from world leaders. Especially world leaders from heavily fossil fuel based economies believe in secure (coal based) electricity generation (World Economic Forum, 2010). Furthermore the focus/value on CCS may grow even more as the cost of mitigation continues to increase as society postpones action (Stephens et al., 2006).

CCS incorporates various technologies and is consistently divided into three main parts; capturing the CO_2 from the flue gas, transportation of the CO_2 to the sequestration site and storage of the CO_2 in suitable underground locations (WRI, 2008). CCS is in particular interest for fossil fuel driven production industry and power plants. CCS has the added value that it preserves within reason the standard of living and the continued use of fossil fuels for the production industry; whilst trying to reduce emissions and limit average global atmospheric CO_2 concentration to 450 ppm in 2050. The IEA energy outlook 2009 states that without rapid CCS deployment this goal is unattainable (IEA GHG, 2009). Despite the ethical debate whether CCS ought to occur, investment in fossil fuel instead of renewable technology, it is assumed that CCS will be integral to the emission reduction portfolio of many nations.

Regardless of the urgency to demonstrate CCS technologies (IEA/CSLF, 2010) and continuously increasing funding, no fully integrated power plants with CCS have yet been built on a commercial scale (de Coninck et al, 2009). Hence, the key concern is how CCS could be implemented on a large scale that is

both economically viable and can significantly reduce CO_2 emissions. In the last few years, some small pilot plants have been constructed but none at the scales needed to cause a real impact. Successful large scale demonstration plants have the capability to not only reduce economic uncertainties but also other barriers. Abridged selections of the main barriers to CCS technologies are:

- **Economic:** its high capital costs and operating costs associated with the energy requirement of capture systems, which reduce power plant thermal efficiency (Cohen, 2009).
- **Regulation:** uncertainty pertaining to future CO_2 emission laws in both its formulation and execution.
- **Ethical:** is CCS just a justification to continue investing in unsustainable and polluting fossil fuels instead off lean renewable technologies. (Greenpeace, 2008)
- **Public acceptance:** ensuring that public opinion, safety and health is taken into account and that CCS can provide continued standards of living (Ramirez et al, 2008)

Although, a brief general summation of the challenges CCS faces, it does provide the key aspects of the wider issues. For instance, each stakeholder will have another priority or goal why or why not CCS should happen. Nonetheless, this thesis proposes that CCS shall ensue and that the focus should be on reducing costs for the capture process. Estimations of the overall CCS costs, preformed by the IPCC (2007) and IEA (2003), contribute 70-80% to the capture of CO_2.

1.2 CO_2 Capture at Coal-Fired Power Plants

Most of the anthropogenic CO_2 emissions originate from power generation, industrial process, transportation and residential/commercial buildings. Power generation accounts for 35% of the global CO_2 emissions (IEA, 2003). Coal-fired power plants account for 60% of power generation emissions. With intensified pressure from governments and public to reduce emissions, these coal-fired plants will have to mitigate their CO_2 emissions. Capturing the CO_2 will reduce their emissions if it can be transported and sequestrated. Under the assumption, that CCS will come to pass; coal-fired plants will have to capture their CO_2 emissions. There are three general techniques for the capture of CO_2 during energy production from fossil fuels; oxyfuel, pre- and post combustion capture. Each approach has their strengths and weaknesses.

Oxyfuel combustion is the separation of oxygen from the air to combust with the fuel and recycled exhaust gasses. This causes the resulting exhaust gas stream, once dried, to consist of 80-98% CO_2; making separating and compression of the nearly CO_2 for pipeline transport and subsequent storage relatively straightforward (Metz, 2005). This type of capture can achieve nearly 100% CO_2 removal efficiency, but the additional CO_2 purification processes still incur some capital and energy costs. Metz states further that including the costs of oxygen from air separation puts the overall economics on par with pre- and post combustion. Oxyfuel systems could be retrofitted to existing coal-fired facilities but with sufficient boiler modifications. However, these systems have not yet been built in a new or retrofitted plant, putting this technology behind pre- and post combustion.

Pre-combustion Capture at coal-fired plants removes the CO_2 from the fuel during gasification and water-gas shift processes prior to the combustion of hydrogen for power and/or heat generation. Furthermore, the produced hydrogen could be used in fuel-cells or as a feedstock for other industrial processes (Metz, 2005). The component parts of pre-combustion technology exist today at commercial scale; the challenge now is to integrate these in a power application. In addition, pre-combustion is not suitable for retrofit of existing coal-fired power plants. This technology will have to be integrated for the design stage of a coal power plant.

Post combustion capture takes place after the combustion process needed for power generation; this tail-end process is attractive for its retrofit option to existing coal-fired power plants. Furthermore, post combustion capture using chemical absorption has been applied is some commercial industrial processes. Even though, the other two approaches to capture may prove to have lower capital, operational and energy costs its ability to be retrofitted to existing coal-fired facilities may be very important if existing coal-based plants are to remain in service throughout their useful life (Metz, 2005). Should society desire a hasty deployment of CCS then post combustion capture at coal-fired power plants is an attractive option. Therefore, in this thesis the option for post combustion capture at coal-fired power plants will be a focal point.

There are several variations of the capture approaches but all have common barriers to implementing them; including high capital, operational and maintenance costs. These high costs and energy penalties associated with the removal of CO_2 from the emissions create an incentive to find cost reductions. Current coal-fired power plants with post combustion capture have business cases that present the same conclusion; at current CO_2 and electricity prices the business case will return a negative Net Present Value. To improve the business case for coal-fired power plants with capture (post combustion capture here forth referred to as capture) different means can be investigated; technological, policy or regulatory.

1.3 Improving the Business Case for Coal-Fired Power Plants with Capture

In general, coal-fired power plants are interested in continued operation and profitability. Knowing that continued operation will be in a CO_2 market; either the existing EU Emission Trading Scheme (ETS) or a derivative of it in the future, it will make losses on CO_2 emissions. Currently, the price for CO_2 is too low for them to warrant investment in capture technologies and buying emission credits is preferred (E3G, 2008). Nonetheless, most believe that the price will rise in the future and are looking at means to reduce investment, operation and maintenance costs for capture. Especially for coal-fired plants, CCS could have negative effects on their current business model. Capture adds an energy penalty of 25-40% and increases the costs of electricity (COE) by a significant amount. This increases variable costs to generate electricity and could impact its position in the merit order. Additionally, coal could lose its current base load generation position to nuclear and renewable and therefore supply more variable demand. To be able to supply variable demand coal-fired power plants will have to be flexible. Coal-fired power plants are currently very inflexible and require slow turn down and ramp up (Lambertz, 2010).

Many of the literature studies are conducted from a decision makers' perspective; this has an advantage that solutions can be stipulated what should be implemented at a specific time to reach a

certain mitigation goal. However, as one of the largest emitters of CO_2, coal-fired power plant owner/operators are also part of the solution. Although incentive programs, regulatory frameworks and top-down governance models have been discussed/developed, one aspect is under expressed. This is which option the coal-fired power plant operator prefers in a post carbon society. The implementation of capture will reduce profitability of a coal plant considerably, if not totally, and therefore consequently unwanted. Nonetheless, coal-fired plant owners/operators realize that in a post-Kyoto world mitigation of CO_2 must happen. To remain competitive a coal-fired power plant will need to become more flexible and apply new techniques. One possibility is the use of flexible operations; this entails strategically choosing to capture or not at times of high and low electricity and or carbon prices. For instance, when the CO_2 price is low and the electricity price is high, capture could be switched off and therefore be able to provide more energy at premium prices. This could reduce investment costs for capture plants considerably (Cohen, 2009).

Three flexible operations called Flexible Operating Mechanisms (FOMs) for coal-fired power plants with post combustion capture are presented/developed in this thesis to reduce the cost associated with the capture of CO_2. However, how these FOMs can improve the business case leads to the formulation of the main research question.

1.4 Main Research Question

How can Flexible Operating Mechanisms (FOMs) improve the business case of an Advanced Super Critical (ASC) pulverized coal power plant with post combustion capture?

This question aims to improve the current business case of coal-fired power plants (ASC pulverized coal in full – referred to as coal-fired plant here forth) through the application of FOMs. The scope of the question covers the techno-economic analysis of a coal-fired plant with post combustion capture for the perspective of a plant operator. In order to answer this main research question in full, 4 sub-questions are posed. After each and every sub-question the scope and methodology to answer each sub-question is described. In addition, the chapter that covers the specific sub-question is mentioned.

Sub-questions:

A. *What is flexibility for pulverized coal power plants and/with post combustion capture?*

B. *How can the operational performance of the Flexible Operating Mechanism's (FOMS) be evaluated with the use of a model?*

C. *Does the model satisfy all verification and validation tests?*

D. *How do different scenarios impact the results of the model and the business case?*

1.4.1 Sub-question A: Flexibility for Coal-Fired Plants with(out) Capture

The aim of this sub-question, found in chapter 2, is to gain a better understanding of the current flexibility of coal-fired power plants. By analyzing the coal-fired plants internal operation and interaction with its environment it will be argued that the flexibility for coal-fired plants is negligible. The introduction of a capture plant, even with the added complexity of integration, could increase its flexibility in electricity supply and response to changes in the electricity and CO_2 markets. For instance, complexity could arise from increase amount of interaction of heat streams between the coal and capture plant. In section 2.3, a more detailed description of the post combustion capture plant is given in order to evaluate its flexibility in relation to a coal-fired plant. Until now the information provided is based on a desktop literature analysis. In section 2.4 the FOMs, partly based on literature research and expert interviews, are revealed and subsequently examined how they could improve flexibility qualitatively for coal-fired plant with capture. The summarized response to the sub-question can be found in section 2.5.

1.4.2 Sub-question B: Evaluating Operational Performance

Where sub-question A intends to provide an overview of the flexible options that a coal-fired plant has or needs; this sub-question's goal is to present a means by which to evaluate the proposed FOMs. In section 3.1 a choice is made for a techno-economic model to calculate the operational performance of the FOMs. The choice of making a techno-economic model is based on the knowledge gap if these FOMs can actually provide additional income. Furthermore, the model will make use of actual electricity prices (on an hourly basis) from the APX. Making use of realistic electricity price data will improve the operational understanding. The methodology used for the creation of the model can be read in section 3.2. This chapter will also introduce the TNO developed reference base case. The FOMs model will be constructed in excel. In the successive sections (3.3 & 3.4) the model is described analytically; including the inputs, variables and equations. The performance indicators, on which the FOMs will be compared, are established in section 3.5. In section 3.6 a synthesis of the chapter, i.e. the response to the sub-question is provided.

1.4.3 Sub-question C: Verification and Validation (V&V)

In chapter 4 a verification (4.1) and validation (4.2) is done in order to ensure that the model can be used for observations about the operational performance of the FOMs. The verification is done using a code verification - checking if the analytical model (chapter 3) matches the translated model in Excel and a calculation verification –checking the numerical errors. The validation consists of a sensitivity analysis for both the base case and the FOMs model.

1.4.4 Sub-question D: Results and Scenarios

After the model has passed the V&V tests, results of the model can be published and interpreted. Initially, the operational performances of the FOMs model are discussed in section 5.1. Utilizing the operational performance (yearly income), at varying CO_2 prices, and the known capital costs (chapter 3) for the required installation, a NPV can be made for each FOM (5.2). These NPV's will show mainly negative

outcomes but can be explained. In section 5.3, future scenarios are presented that reflect possible changes in electricity price and CO_2 trajectories. Section 5.4 will present the results of these scenarios on the FOMs and observations are made about the comparative performance between them. Additionally, the NPV is divided by the capital costs to provide present potential investors with further information. In the last section of the chapter, 5.5, a synthesis is made.

In chapter 6, a summary of conclusions and recommendations, concerning all sub-questions and especially the main research question are reported. Finally, this thesis will include two Appendices: a detailed analysis of the electricity prices provided by the APX through the Utrecht Copernicus Institute.

Chapter 2 *Flexibility for a Pulverized Coal Power Plant and Post Combustion Capture Plant*

The goal of this chapter is to answer the following research sub-question A: *what is flexibility for pulverized coal power plants and/with post combustion capture systems?*

This chapter will analyze how flexibility plays a role in operating coal-fired power plants and post combustion capture plants. In section 2.1, the focal aspects of this research will be reiterated and basic assumptions of the surrounding environment are made. In section 2.2, an assumed future operational environment is expressed in which coal-fired power plants will have to operate. In this future environment CCS plays a pivotal role and capture will have to be implemented by coal-fired plant operators. Capture (post combustion capture) plants offer more flexible opportunities that will be examined in section 2.3. In section 2.4, several Flexible Operating Mechanisms (FOMs) for a post combustion capture plant are described. Followed by section 2.5, where a means to examine the techno-economic performance is suggested. Finally, the chapter ends with a synthesis (2.6) and next steps in the thesis are presented.

2.1 Pulverized Coal Power Plant Operational Environment

In section 2.1.1, the current operational environment will be described and in 2.1.2 the internal operation of a coal-fired power plant is illustrated. This is followed by section 2.1.3 where the operational flexibility of a plant is examined.

2.1.1 Current operational environment

Currently coal power plants operate in a pre-CCS environment and the only measures to technically limit emissions are those imposed by the SO_2 and NO_x regulations. CO_2 emissions are still permissible; however a financial tax must be paid. This is currently done through the European Union Emission Trade Scheme (EU ETS). Anthropogenic CO_2 emissions to the atmosphere must be paid in the form of Carbon Emission Rights (CERs).

Coal fired power plants are one of the largest producers of energy worldwide. Being one of the cheapest and most abundant fuels it is economically attractive to use them as base load electricity producers. This means coal plants are able to operate continuously and therefore provide a constant electricity supply to the grid; with exception of planned maintenance or unplanned events halting operation. However, coal-fired power plants do operate with a changing load profile. This will be explained further the section 2.1.2.

Coal-fired power plants sell their electricity by two means; bilateral contracts and on a liberalized spot-market (APX). Bilateral contracts are those between the power plant and single large clients. In contrast to the public consumer, whom is highly inelastic, these large industry parties are more elastic in their purchase behavior. This means that changes in electricity prices don't affect the electricity usage of consumers; i.e. demand remains the same even if prices rise strongly. In relation to coal-fired power plants this means that public consumers will continue to demand electricity but that large clients may

change to cheaper providers. In the future consumer behavior might change, nevertheless, for now it is assumed that they remain inelastic.

2.1.2 Pulverized Coal Power Plant internal operation

This thesis makes use of a reference base case coal plant; this is an 800MW Advanced Super Critical (ASC) pulverized coal power plant. ASC coal-fired power plants are currently the most built type of coal plant. By pushing the steam conditions to higher levels, the efficiencies of pulverized coal plants have increased considerably in the past decades. In addition, these efficiencies will increase even further in the decades to come. Limits on the maximum attainable steam temperatures and pressures are determined by the materials of the boiler and the blades of the steam turbines (Beér, 2006). As name suggests, coal-fired supercritical power plants operate at very high temperature and pressure (580 degree centigrade temp. with a pressure of 23 MPa) resulting much higher heat efficiencies (46%), as compare to sub-critical coal-fired plants which operates at 455 degree centigrade temp., and efficiency of within 40%.
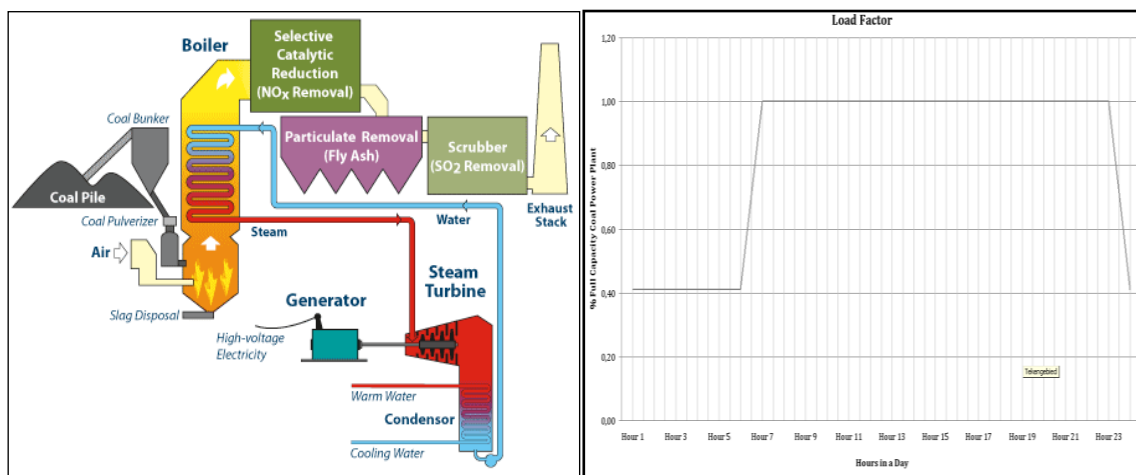
Figure 2-1 (left) Internal Operation Advanced Super Critical (ASC) Pulverized Coal (PC) Power Plant; (right) Load profile 1000 MW coal Plant (E.On Benelux)

Another important factor that influences the electricity output of the coal plant is the load profile. During night hours the overall demand for electricity is lower and this is reflected in the amount of electricity required from the plant. In figure 2.1 (right) the load profile of 1000MW E.On Benelux Maasvlakte plant is illustrated; this graph was provided by E.On Benelux. Although the thesis utilizes a different size plant the capacity factor will remain the same. Therefore, it can be stipulated that during off-peak times around 41% of total capacity is provided to the grid.

2.1.3 Modes of flexibility for pulverized coal power plants

Before exploring the technical details of a coal-fired plant with capture, it needs to be understood which types of flexibility may be required or useful for any coal-fired plant operator (Chalmers, 2009) constructed a table, 2.1, that describes the main modes of flexibility for power plants that are interesting for plant operators. Some of the flexible aspects are already in place and others are currently less feasible due to technology constraints. These modes of flexibility will be compared to the modes of flexibility of Post Combustion Capture (PCC) plants; this will be done in section 2.3.3.

The modes of flexibility for coal-fired plants are limited, as shown in table 2.1, nonetheless the need for flexibility is increasing as the operating environment alters, presented in section 2.2. The most modern plants are increasingly capable of integrating flexibility into their operating portfolio. However, most current coal-fired power plants are built to run as base-load installations; and therefore aren't designed with these additional flexibility options. Furthermore, the selection for post combustion capture was based upon its capability to add-on to existing power plants (retrofit capability). Even though, state of the art coal power plants can integrate more flexibility, most plants that CCS will be used for are older with less to no flexibility. It is these kind of older plants that are most abundant and therefore, the focus of this paper will be on existing coal power plants.

Table 2-1 Some Aspects of flexible Operation desirable for coal plants (Chalmers, 2009)

Mode of Flexibility	*Motivation and Value*
Quick start-up/shutdown	For providing support services, it is valuable to have some plants that are able to respond rapidly to changes in demand or failures at other power plants. Start-up and shutdown can be expensive as the plant is operating at suboptimal conditions. Furthermore thermal stressing could reduce lifetime of the plant.
Quick change in output (up or down)	Fast change in output can provide auxiliary services in response to changing demand or supply elsewhere in the network. Changes in output at plants that are already operating can be important for immediate response until other plants in the grid are started up.
Effective operation at part load	For plants that are operating below their designed capacity so that they are able to ramp up quickly, it is clearly important that they are able to operate as effectively as possible at part load so that they cost of providing this service (and/or lost profits to plant operator) are minimized.
Increase in maximum output	Some plants are able to operate above their normal maximum output when required, possibly at lower efficiencies or with negative effects.
Decrease in minimum output	Some plants run at a trading loss overnight if electricity prices are below marginal generating costs but they are kept running to avoid the costs of an additional start-up/shut-down. It can be beneficial to reduce the plant's output to reduce operational costs. This is seen in the load profile in section 2.1.2.
Ability to use different fuels (including biomass)	Being able to switch between fuels can be important for ensuring a reliable supply at reasonable prices.

From table 2.1, one can see some flexibility but with limitations. Start-up and shutdown procedures for coal power plants can take up to 24 hours to ensure minimal thermal stressing whilst cooling of the equipment. Overall, one can state that for quick hourly changes in the electricity market, those current coal power plants can be assumed "inflexible".

2.2 Future operational environment

As presented in the introduction an expected shift towards CCS will need to be taken to reduce CO_2 emissions to the atmosphere. This future operational environment, in which coal-fired plants will need to operate, will require the operators to alter their behavior and mindset. Currently the CO_2 prices are low enough to warrant inaction and compensate with financial means; i.e. pay the tax. However, should prices

rise higher a trade-off will need to be made and invest in reducing CO_2 emissions; i.e. capture technology. In the introduction, the choice has been made for post combustion capture (PCC); a more technical detailed description of a PCC plant is presented in the next section.

Regulations will inevitably also change; the European Commission has taken several initiatives to ensure the coherent implementation of the CCS Directive throughout the EU. As well as funding several pilot/demonstration projects, further research is also done on each field within the value chain of CCS. Moreover, the EU has committed its member states to achieve 20% more renewable energy and 20% reduction in emission by 2020. If this is realized, it is likely that flexible operation of most or even all fossil fuel plants could become virtually obligatory in many plausible lower carbon electricity mixes (Chalmers & Gibbons, 2009). The increase in renewable (i.e. wind/solar) and nuclear power generation typically have lower marginal generating costs than coal. These could then encroach on the base-load generation position of fossil fuel based power plants, but they will not be able to provide auxiliary services (especially renewable with intermittency – wind/solar). Consequently, there may be significant periods that require fossil fuels power plants to maintain system security.

Overall, one can state that the future operating environment for coal plants is uncertain and dynamic. To survive in such a market, flexibility and/or robustness will be required; i.e. increase the ability to cope with altering situations. In the next sections, the integration of post combustion capture to a coal-fired plant is described technically and how this addition could increase the overall flexibility of a PC plant.

2.3 Post Combustion Power plants

In 2.3.1 the internal operation of a post combustion capture plant is described. This is followed by section 2.3.2, where the impact of integrating a coal power plant with post combustion capture is examined. The addition of a capture plant present challenges but also operational opportunities. These operational opportunities can be found in the flexible modes of a capture plant. The different aspects of flexible modes are presented in section 2.3.3.

2.3.1 Internal Operation Post Combustion Power plants

The capture of CO_2 from the flue gasses by the combustion of fossil fuels is referred to as post combustion capture (PCC). The flue gasses from a power plant originate from the combustion chamber where hot gasses and steam are generated for use in a generator; see figure 2.1. Normally, before emitting the flue gas to the atmosphere the soot, Nitrous Oxides (NO_x) and sulphur dioxide (SO_2) are subsequently removed. In the case of PCC, additional sulphur dioxide will have to be removed to protect the absorption solvent; typically an amine, e.g. mono-ethanolamine (MEA). In this thesis MEA is used for two reasons; first, it's the most mature/commercial solvent and second, MEA is used by most researchers when discussing the potential of post combustion capture.

In figure 2.3, a schematic representation of a typical PCC plant is shown. The cleaned flue gas is passed through an absorber where the CO_2 containing flue gas is contacted with MEA. The CO_2 is absorbed by the solvent and the remaining flue gas is vented to the atmosphere. The solvent is now referred to as "rich" and transferred to the scrubber column where a reboiler is used to provide the heat necessary to

release the gas from the solvent. The CO_2 is collected, dried and compressed to prepare it for transport to a safe geological storage site. The regenerated solvent is now "lean" and is sent back to the absorber to be reused. Typical reboiler temperatures for 30% by weight MEA-based solvents are around 120°C (Gibbins and Crane, 2004). Should the capture plant be turned off, as suggested later, this temperature must be maintained in order to complete a hot start. If the temperature should drop in the reboiler then it must be reheated before the capture process can begin. In 2.4.1, the differences of hot and cold starts are explained in more detail.
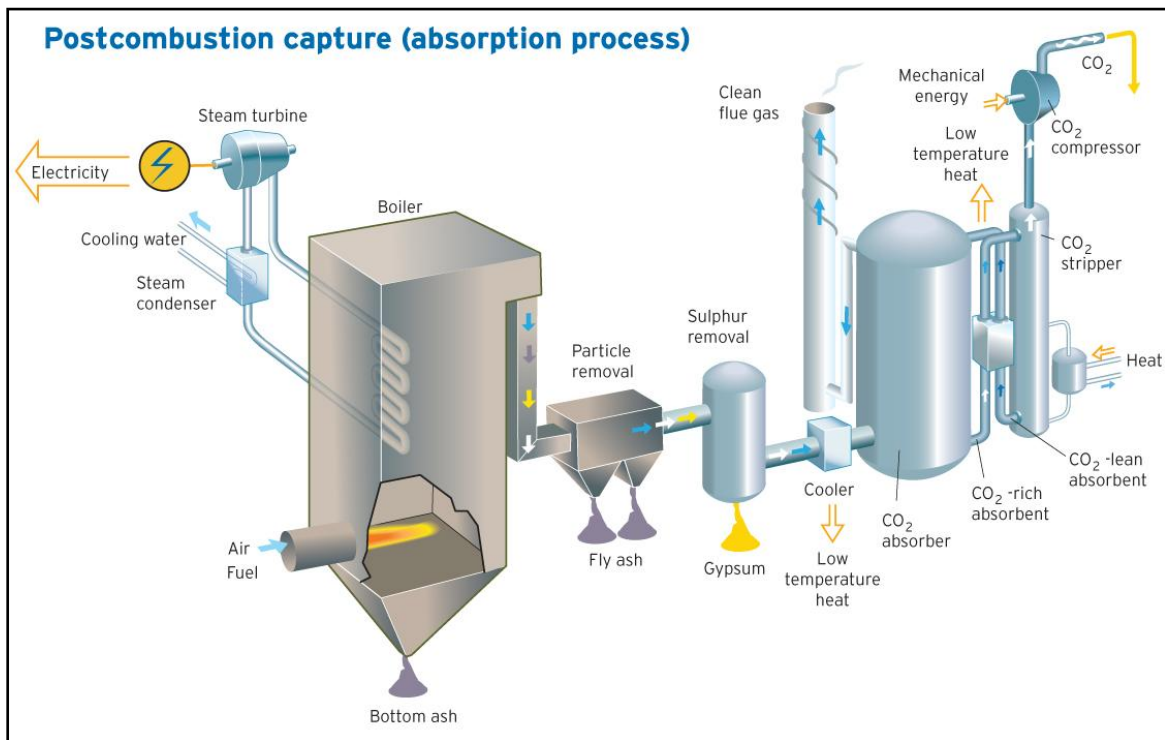
Figure 2-2 schematic representation Post Combustion Capture (IEA, 2003)

The proposed capture system is considered as one of the most mature capture methods, since there is a good experience and reputation of this technology within many industrial applications (Rao & Rubin, 2002 & Cohen, 2009). However, Post combustion capture is evolving rapidly; new solvents are being tested in order to reduce costs. Moreover, increased system integration between the coal plant and post combustion capture plants as well as with other industrial partners could reduce the energy penalty inherent to any capture technique.

2.3.2 Pulverized coal power and post combustion capture integration

For coal-fired plants, that will be the main focus of the thesis, it has been shown and now generally accepted, that the most efficient method for providing the low heat required, for the reboiler, can be extracted from the intermediate and low pressure turbines in the steam cycle (Gibbins et al, 2004). Furthermore, the steam is condensed and reused into the coal power plants boiler. By integrating heat streams from the coal plant to the capture plant, the efficiency of the power plant with capture increases in relation to no integration. The integration of the plant with capture will generally increase the number of interactions and integration paths between the units. Moreover, it will likely increase the internal

complexity and possibly impact flexibility as a whole. However, initial analysis suggests that this may not be the case for post combustion capture plants (IEA Greenhouse Gas R&D Program 2004). Although internal complexity rises it will also increase the external flexibility (described in more detail in section 2.3.3).

All things considered, the high energy requirement make the capture processes energy intensive and hence costly. However, under the premise that CO_2 prices will rise, action needs to be taken. The integration of a capture plant with a coal-fired power plant also creates opportunities. The natural "inflexibility" of coal power plants can decrease through the flexible operation of the capture installation. For instance, by switching the capture plant off during peak energy demand hours, an additional electricity output can be generated. Consequently, peak demand prices tend to be higher and therefore more income could be generated. Furthermore, this on or off switching of the capture plant could mean that the coal plant could add more auxiliary services to the network. As intermittent renewable sources, such as wind and solar, lack this capability it may provide coal-fired plants with capture with a competitive edge.

2.3.3 Flexibility through Post Combustion Capture

The addition of capture to a coal fired power plant can create new operational choices; forming modes of flexibility. In table 2.1, the modes of flexibility, first described by Chalmers (2009) in context of coal-fired power plants, are applied to a capture plant with post combustion capture, in table 2.2.

<div align="center">

Table 2-2 Some Aspects of flexible Operation of PC plants with capture

</div>

Mode of Flexibility	*Mechanism and Value*
Quick start-up/shutdown	There are two types of start-up/ shut-down procedures a PCC can do; 1. a hot start can be referred to as a standby state. The temperature in the reboiler remains the same. This could make switching between zero (off) or full (on) load plausible in 15 to 30 min, 2. A cold start is from a complete stop to full load. This includes re-warming of the reboiler and can take up to a few hours (Delarue, 2011)
Quick change in output (up or down)	Through operation manipulation of the capture installation, reasonably quick changes in output can be realized without changing the output of the coal plant itself. This is advantageous for the coal plant as it can maintain its current operation.
Effective operation at part load	In particular, solvent storage could allow for higher effective plant load factors to be achieved assisting with capital recovery while still permitting flexible operation for grid support (Chalmers, 2007).
Increase in maximum output	Should the power plant increase its maximum output then capture is able to ramp up with it. However, this will be at an added cost deviating from the designed optimum. I.e. Only for short time intervals can both the coal and capture plant increase its processes. However, this is not desired in terms of equipment longevity.
Decrease in minimum output	It might be possible that the capture plant will be designed to tolerate a certain minimum flue gas flow rate, e.g., 40% of the rated flow rate. Under this flow rate, the capture plant cannot maintain its stable operation. Hence, this might influence the minimum operating point of the power plant, if this is initially lower than 40%.

Ability to use different fuels (including biomass)	This should have no strong effect on the operation of the capture plant if the flue gas remains within operational quality. In addition, the use of biomass will reduce the environmental impact. In combination with CCS this would lead to a "negative" CO_2 emission. Although outside the scope of this thesis it's an interesting option.

Instead of a motivation it describes a potential capture mechanism that could improve the operational flexibility of the whole system.

After analyzing the desired modes of flexibility for power plant operators in table 2.1 and identifying which modes of flexibility for coal plants with capture could add, in table 2.2, a list of possible mechanisms can be identified that warrant further attention. These flexible operations will be referred to as Flexible Operating Mechanisms (FOMs) for the remainder of this thesis. In section 2.4 the FOMs are presented and explained both technically and on their qualities / limitations.

2.4 Flexible Operating Mechanisms (FOMs) for PCC plants

In the previous sections some of these FOMs have been mentioned in examples and/or discussed as possible means to increase flexibility of a coal plant with capture. In this segment, the three main FOMs are presented. The 3 flexible operating mechanisms are:

1. Capture ON or OFF   (section 2.4.1)
2. Partial Capture ON or OFF   (section 2.4.2)
3. Intermediate Storage (always ON)   (section 2.4.3)

For each FOM a technical description is given, including requirements to apply the technology, as well as an account of advantages and limitations of each mechanism. At the end of the descriptions a summary of the FOMs strengths and weaknesses are presented in table 2.3.

2.4.1 Capture ON or OFF

Capture ON of OFF may seem straightforward; however, a differentiation must be made. Capture ON means that the capture plant is at full load and all components are functioning as designed. Capture OFF can have two meanings; either switching the capture ON mode to a hot or a cold state. The hot state refers to a standby mode; flue gas from the coal plant is emitted directly to the atmosphere, absorber and strippers halt function but the reboiler remains at rated pressure and temperature. The other capture OFF mode could be a transition to a cold state; the same as a hot state however the reboiler heating is also turned off. The difference between the two states is the start-up / shut-down times. For quick switching (hourly) between ON and OFF, a hot state is preferred; for longer intervals (more than a 12 hours) a cold state is deemed more economic (Cohen, 2009). Although to the author's knowledge, no studies have been done to calculate the optimum timeframe at which preferred hot or cold state occurs. The expected advantage of this FOM is that at low CO_2 and high electricity prices the capture plant could be turned off and that the unused energy penalty could be utilized to generate additional income.

No foreseeable large additional equipment (investment) is necessary to apply this FOM besides the initial investment of the capture plant; a valve will be located prior to the capture plant that allows for venting flue gas directly to the atmosphere. Without additional equipment the application of this FOM is

inexpensive and reasonably effortless to operate. Nonetheless, a limitation could be that future regulations stipulate a reduction quota; this would in effect reduce the value of this FOM. Furthermore, contractual obligations to transport parties, those transporting the CO_2 from the source to the storage sink, could mean that turning off is not as feasible as previously thought. Transport parties would require a steady stream of CO_2 to keep pipeline pressures high enough to ensure a constant driving force. The absence of clearly understood integration principles between capture and transport parties creates unknowns that will have to be examined in more detail. However, his interaction is outside of the scope of this thesis.

2.4.2 Partial Capture ON or OFF

Partial Capture refers to the scale of the capture plant in relation to the feeding coal plant. For instance, a 40% partial capture plant in conjunction with a 1000MW coal-fired power plant is defacto a 400MW capture plant. Technically, not a Flexible Operating Mechanism, however on an operational level (operational costs) it is at par with a 100% capture plant running at 40% load capacity. In relation to the capture ONorOFF, this FOM requires more than just operational foresight and planning. The decision to invest and construct a smaller capacity capture plant will need to be made near the beginning of the design phase. In chapter 3 it is proposed to study 3 different scale sizes in relation to a full scale version; 80, 60 and 40% partial capture plants. Similar to capture ONorOFF this FOM will also have the capability to turn on or off depending on prices. The expected advantage of partial capture is that it will be more operational at lower CO_2 prices; hence a smaller plant could start reducing CO_2 emissions and generate revenue much sooner than larger scale version. Its limitations are also its size; should CO_2 prices raise more rapidly than expected then capacity will need to be added.

The technical requirements will differ according to the scale chosen; larger scale plants will need larger equipment vis-à-vis higher investment costs. The effects of economies of scale on capital and operational costs will be analyzed in chapter 3, section 3.4.

2.4.3 Intermediate Storage

This FOM aims to maximize the income from electricity by turning off the stripper and compression (reducing the energy penalty of capture) at the moment electricity price peaks. During this time the rich solvent is stored in a tank, while lean solvent is retrieved from a different storage. This process is also known as intermediate storage. Intermediate storage can be done with different time frames; this thesis will focus on a maximum of 4 hour storage and a minimum of 1 hour. At high electricity prices the capture process will halt stripping and compression to gain an extra electricity to be sold. At low load more stripping and compression will be needed; i.e. the capacity of the capture plant will have to be designed to cope with this additional rich solvent. However, as the maximum storage time is 4 hours and the low load period lasts 7 hours it is assumed that the surplus CO_2, in relation to "normal" operation, can be done in this time frame. Should it occur that the additional solvent cannot be processed in this time then it should be decided to store for less hours. However, the assumption that it can be done within the low load time frame will stand for the remainder of this research.

This FOM will require investment in extra equipment and space; 2 storage tanks, additional solvent (MEA) and additional space to place the tanks. Moreover, levies should be built to protect the surrounding environment against spillage. The expected advantage is that the plant may be able to sell extra electricity at high electricity prices without emitting CO_2 to the atmosphere.

2.5 Comparison FOMs

In the previous sections, the three main FOMs have been examined individually; in this section they will be compared on their qualities and expected advantages.

Table 2-3 Advantages, disadvantages and requirements FOMs

Flexible Operating Mechanism	Advantages	Disadvantage	Additional Requirements
Business as Usual (BAU) – No Capture	▪ No change in operations	▪ Continued incurred CO_2 costs without minimizing options	▪ None
Capture ON or OFF	▪ Avoid energy penalty at favorable prices, i.e. sell more electricity ▪ Cheap and effortless to apply to current process	▪ CO_2 costs will be incurred at times capture is off,	▪ Valve to vent flue gas prior to capture
Partial Capture (80, 60 & 40%)	▪ Become operational at lower CO_2 prices ▪ Faster investment payback time at lower CO_2 prices	▪ Early design decision ▪ Could become obsolete at a given CO_2 price requiring additional capacity	▪ Redesign of the capture plant prior to construction
Intermediate Storage (1,2,3 & 4 Hrs)	▪ Gain extra income at high electricity prices ▪ Keeps capture rate of 90% ▪ No extra CO_2 emissions	▪ Additional land space is required ▪ Increase stripper and compression capacity	▪ Storage tanks and land space ▪ Additional Solvent

In chapter 3, the options will be studied in greater detail; including analytical analysis of the FOMs, effects of economies of scale, dimensions of equipment needed. However, before discussing the means in which the options will be studied an overview of the FOMs are shown in table 2.3. Having analyzed the FOMs qualitatively it is important to gain quantitative information about the FOMs. In chapter 3 the FOMs will be expressed analytically and how they can be evaluated. The goal of the evaluation is to analyze the techno-economic performance of each FOM.

2.6 Synthesis

The goal of this chapter was to answer the research question; *what is flexibility for pulverized coal power plants and/with post combustion capture systems?* This question can be separated into two answers; the first relating to flexibility at coal plants and the second towards capture plants. It has been established that coal power plants are rather "inflexible" to react to quick changes in operational environment. It has been suggested that in a future operational environment, CCS will play a large role in the mitigation of CO_2 emissions. In effect, coal plants will have to capture their emissions and therefore capture becomes part of "normal" operation. Nonetheless, capture plants can add additional operational flexibility to the coal plant

to reduce the financial burden that is inherent with capture technologies. Furthermore, proposed Flexible Operating Mechanisms (FOMs) show promise in reducing operational costs and possibly reduce overall payback times of the capture investments. Therefore, capture adds additional flexible options for coal plant operators to provide, for instance, auxiliary services. In chapter 3, a model is proposed that can calculate the operational performance of the FOMs and aid in evaluating them.

Chapter 3 *Evaluating Flexible Operating Mechanisms*

The goal of this chapter is to answer sub-question B: *how can the operational performance of the Flexible Operating Mechanism's (FOMS) be evaluated with the use of a model?*

This chapter introduces a techno-economic model to evaluate the FOMs; moreover, this chapter will present the model analytically. In section 3.1, the choice for constructing a model is given as well as the aim and characteristics of the model. In 3.2 the inputs for the model are discussed and shown; these include the general inputs, extrapolated and adapted data and the variable inputs. Next, in 3.3, the NO capture model is explained; i.e. the model shows the coal plant's performance without capture. In segment 3.4 the FOMs models are explained. After the models and sub-models are described, in section 3.5, the performance indicators of the model are discussed; i.e. from initial operational performance to FOMs NPV over the lifetime of the capture plant. The NPV is utilized to calculate the cost benefit ratio (CBR) for investors. Finally, section 3.6 presents a synthesis of this chapter.

3.1 Evaluating FOMs

This section will present the motivation for a model and subsequently, the aim and characteristics of the model. In section 3.1.3 the model methodology is established.

3.1.1 Motivation for a Model

In chapter 2, several flexible operating mechanisms have been identified and qualitatively described. The FOMs show promise but no exact statements about their performance can be done. In the literature, Cohen (2009) discusses the effect on the ERCOT grid with the use of flexible operation of capture (ON or OFF) and Chalmers (2007) presents possibilities of flexible operations to reduce the financial burden of capture. To the authors' knowledge, no techno-economic analysis of the operational performance of capture plants employing FOMs has been developed. The operational performance is expected to be dependent on the electricity and CO_2 prices. To compare the FOMs a model will be developed to calculate the operational performance.

3.1.2 Aim & Characteristics of the Model

The aim of this model is to evaluate the various FOMs, as described in 2.4, which can be applied to a coal power plant with capture. Furthermore, the model will act as a comparative tool between capture always ON and various FOMs and present the user with outcomes dependent on the chosen variable inputs. Finally, the models aim is to be adaptive and function under different scenarios. These scenarios will consist of altering the inputs to match a probable future; these scenarios are discussed in chapter 5.

The characteristics of the model can be expressed as a bottom-up, retrospective, deterministic and dynamic model. A "Bottom-Up" analysis incorporates an engineering perspective and process modeling to determine and optimize the functioning of both the PC power plants and the PCC plant; i.e. all the operational (OPEX), capital (CAPEX) and equipment costs are included into a discounting cash flow analysis to determine the total plant capital (TPC) costs and cost of electricity generation (COE). The model is ex-post facto; a retrospective examination of a coal-fired power plant with/without post

combustion capture. Hence, studying whether the implementation of FOMs increases the business case of coal plant with capture or not. Moreover, the decision to invest has been made prior to simulation. In other words, the model calculates the operational benefit of the FOMs. The model is deterministic and therefore doesn't rely on chance events such as breakdowns or planned maintenance. Last, the model can be characterized as dynamic; making use of hourly electricity prices and changing CO_2 prices that model is less static than preceding steady-state techno-economic models.

3.1.3 Model Methodology

This model will be built in Microsoft Excel. In the following sections the inputs for the model are discussed. The calculations in this chapter are mathematical of nature but are translated to function in Excel. Macros have been written to create simulation runs. The simulation run will calculate the performance of a given FOM at a given CO_2 price. By varying the CO_2 price through multiple simulation runs the performance at any given CO_2 price can be illustrated graphically. The manual for the FOMs model can be found in Appendix B.

The Flexible Operating Mechanisms (FOMs) model consists of 3 different models. Each of these models can be divided into sub-models. In figure 3.1, the model setup is illustrated.
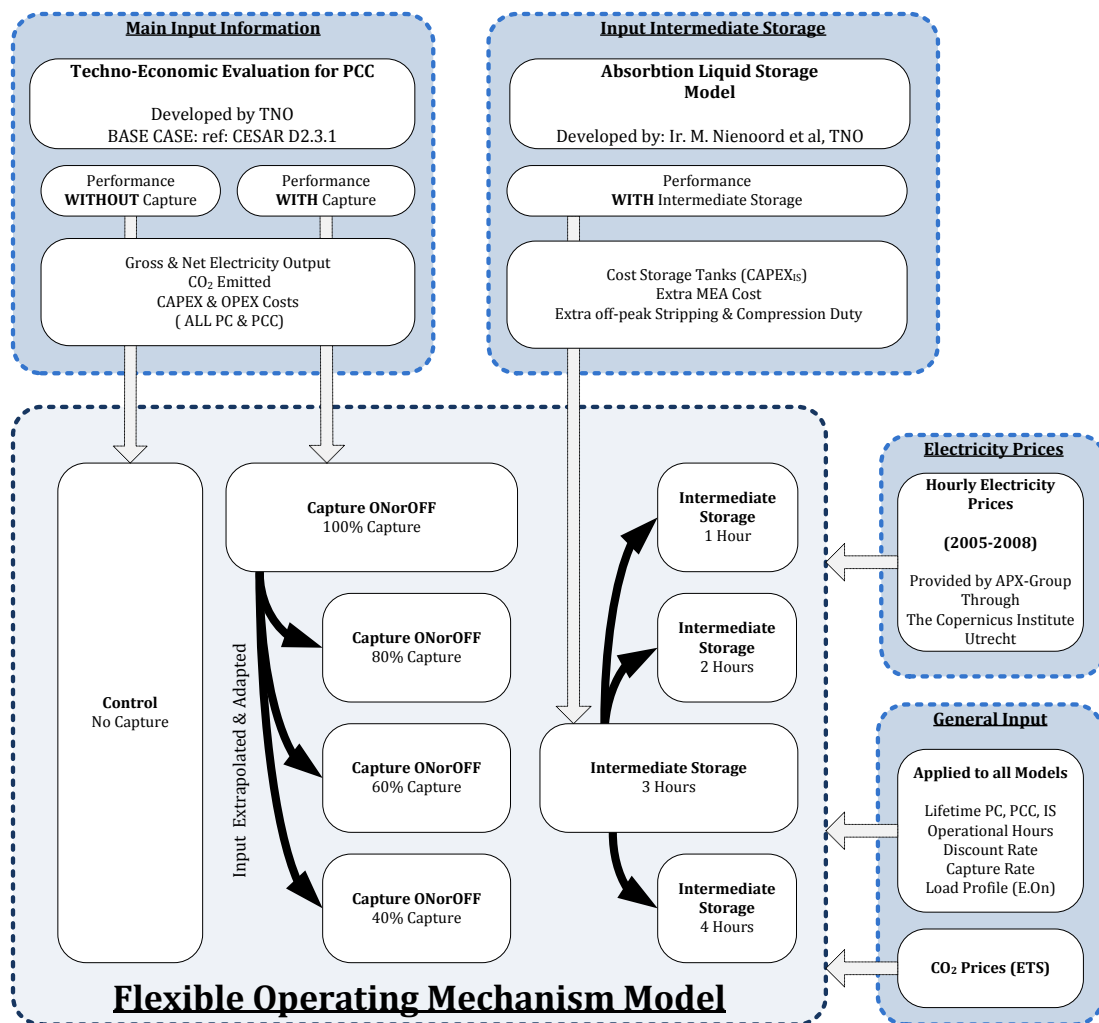

Figure 3-1 Model structure – interdependencies between the models is visualized

The model uses several inputs from different sources, as shown in figure 3.1. The FOMs model itself, to be calculated in Excel, consists of the equations and constructs described later in this chapter. The choice for Excel was based on its capability to analyze the behavior at each timeframe. Furthermore, using Excel is useful for keeping an overview of the inputs, outputs and calculations. In the subsequent sections the rules for each FOM are also expressed; i.e. at which electricity and/or CO_2 prices should the capture be turned OFF or ON.

The model has already been characterized as a comparative tool to calculate the operational performance of the FOMs retrospectively over a 4 year period. From the hourly operational performance an average yearly operational performance can be computed. This yearly operational performance, at a stable CO_2 price over the 4 year period, can be used to calculate a NPV for a coal plant with capture using a specific FOM. Varying the CO_2 prices, the strengths and weaknesses of the FOMs under different CO_2 prices can be studied. Understanding that the business case is a negative one, the aim will be to find FOMs that can reduce the costs; i.e. reduce the negative NPV. Additionally, the report presents investors with the value of the FOMs, by dividing the NPV with the initial investment costs; i.e. presenting the value of every invested euro.

In chapter 5, scenarios will be used to alter the electricity price trajectory; i.e. increased renewable energy source can lower the average price of electricity but due to higher intermittency create larger electricity price fluctuations. This will have a different impact on each FOM individually.

3.2 Input Data

This section will present the input values for the model. First, the general inputs will be discussed, followed by the adapted and extrapolated data from TNO developed models in 3.2.2, the time dependent inputs, CO_2 and electricity prices, are discussed in 3.2.3. The presentation of the results of the models is found in chapter 5.

3.2.1 General Inputs

The general inputs are those inputs that will remain the same for all the sub-models. These include the lifetime of the coal and capture plant, the amount of operational hours, the capture rate of the capture plant and the base-case cost data. The reference base-case design is an ASC 800 MW developed by TNO for the CESAR D2.3.1 work package. This includes the calculations for both a 800MW coal plant with and without capture. The general inputs are presented in table 2.1. From table 2.1 one can see that the plant runs every hour of the year; the decision was made to assume maximum operation as the provided electricity data was continuous. This will be discussed in more detail in paragraph 3.2.3.

Table 3-1 General Inputs for all models

Input	Value	Units
Lifetime PC	40	Yr
Lifetime PCC	25	Yr
Operational Hours	8760	Hrs/yr
Capture Rate PCC	86	%

The reference base-case presents the model with the following inputs for both a coal plant without and with capture; capital costs (CAPEX), operational costs (OPEX), electricity (net & gross) output and CO_2 emitted & captured. The reference base case input information is expressed in table 3.2. The values are non-cumulative; for instance, the <u>value with capture is the additional cost of adding a capture unit</u>. For the electricity output the value includes the energy penalty by adding a capture unit to a PC power plant. The CO_2 emitted with capture is the overall emitted amount.

Table 3-2 Reference ASC 800MW base-case input information

Input	Without Capture	With Capture	Units
Fixed Capital Costs (CAPEX)	1,456.18	203.00	M€
Operational Costs (OPEX)	169.00	29.20	M€/yr
Gross Electricity Output	819	684	MWe
Net Electricity Output	754.30	549.60	MWe
CO_2 Emitted	763.00	104.76	Kg/MWh
Overall Efficiency	45	33.4	%

The CAPEX cost for the coal plant is calculated from the total plant capital (TPC); this includes all the buildings, components, equipment and land costs. The CAPEX costs for a coal plant are in the same order as estimates from Singh and Rubin (2002). The CAPEX with capture consists of the investment costs for the capture plant itself. The total capital investment (TCI) of the capture plant consist of the total purchased equipment (includes amongst others absorbers, strippers, condensers, scrubbers and CO_2 compressors), the total direct plant costs (includes erection, steel, piping and civil works costs) and the indirect costs (including service facilities, supervision and buildings). The operational costs (OPEX) of a capture plant without a capture unit contains the costs for fuel (around 3€/GJ), labor, utilities and maintenance. The OPEX cost with capture adds additional costs besides the extra costs for labor, maintenance and utilities. Roughly 35% of the direct production cost is MEA (Abu Zahra, 2009).

Adding a capture unit has a major impact on the overall efficiency of the power plant. The efficiency will drop from 45% for the reference coal plant to 31% for the reference coal plant with capture. The main efficiency loss can be associated with the additional heat that is required for solvent regeneration (± 55%). The other losses are evenly spread between CO_2 compression and process pumps. These losses can be directly witnessed in the lowering of the electricity output. For both gross and net electricity output, the operation of the capture plant has an energy penalty, therefore reducing the overall electrical output.

In most circumstances the cost of CO_2 would fall under OPEX costs. However, during this research the CO_2 costs will be analyzed separately and individually. The reference base case emits around 763kg of CO_2/MWh. At a given CO_2 price (€/ton CO_2) this would translate into a cost that will have to be incurred. The inclusion of a capture plant reduces the emitted CO_2 to the atmosphere significantly and consequently reducing the CO_2 costs. The price of CO_2 will be a time dependent input and is discussed in the paragraph 3.2.2.

3.2.2 Time dependent inputs

The two time dependent inputs that the model utilizes are the price of electricity and CO_2. First the price of electricity will be examined and subsequently the price for CO_2. Finally the Cost of Electricity (COE) and the Cost of Avoided CO_2 (COA) for without and with captured are tabled.

Electricity Prices

The electricity prices in many preceding models are either flat or make use of a daily averages. In either case they misrepresent the actual electricity price market. As this model focuses on a coal plant situated in the Netherlands it will have to sell its electricity on the APX; this is a spot-market where energy is traded hourly. All electricity producers will offer their electricity to this market at a given price (€/MWh); this price is normally submitted at the marginal generation cost of the given plant. The market will set the hourly price for the electricity; this translates into higher prices at scarcity and lower prices at surplus. By using these electricity prices (APX) it is assumed that the coal plant will only supply through the APX. Bilateral contracts with big parties are excluded. The model will therefore make use of hourly electricity prices to examine the ex-post facto performance of the FOMs.
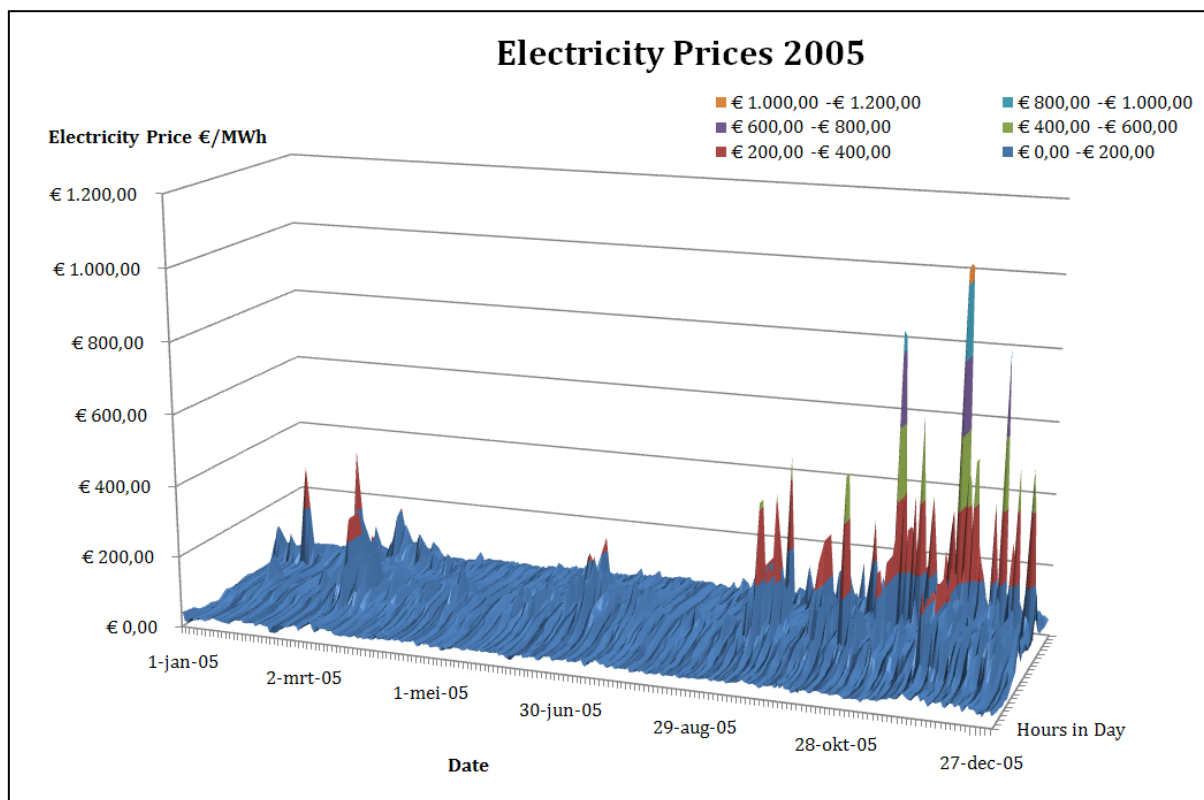
Figure 3-2 Electricity prices during 2005 (APX)

The APX-group provided hourly electricity price data through the Copernicus Institute Utrecht for the period 2005-2008. This large data set of prices makes it possible to asses' hourly performance of the FOMs. In figure 3.2, a segment of the data set is illustrated; the graph shows the electricity prices for the period January 2005 - December 2005. More in detail analysis of the electricity prices can be found in Appendix A. From the graph, one can see that the electricity prices fluctuate significantly and can reach

high to very high prices. In many regimes, price fluctuations are driven by changes in consumer demands and shifts in marginal costs (e.g. fuel) of the marginal power provider. However, in the graph one can see peaking electricity prices that are much larger than the COE for any electricity producer. Causes for this can range from reduction in capacity through unplanned maintenance forcing plants to close, natural events and other circumstances that reduce supply to the market. When these electricity price peaks appear frequently and with less time between them it could be a signal for investors to install additional capacity.

The future development could impact the current prices used by the model, nonetheless the electricity prices present a valuable data set that could be used for a retrospective model to examine the performance of various flexible operating mechanisms. Since the data set is hourly and continuous, the decision is made to exempt the model from breakdowns or non-operational events. This causes the outputs to be idealistic rather than realistic; nonetheless, the model aims to compare the FOMs and therefore it can be assumed, should all the models be tested under the same conditions, that a comparative study can still be valid.

Carbon Dioxide Prices

The European Union Emissions Trading Scheme (EU ETS) is currently in its 2nd phase. Currently, installations get the trading credits from National Allowance Plans (NAPs); which is an entity of each national government. Should an installation perform better, i.e. reduce its CO_2 emissions, and then this installation could sell its surplus credits and generate additional income to offset the investments made to reduce the emissions. Under the EU ETS other mechanisms prevail; these include Joint Implementation (JI) and Clean Development Mechanisms (CDM). However, these mechanisms aren't applicable to the model. During the first half year of 2011 the prices for CO_2 hovered around €15-€16 per ton CO_2. In phase III the energy generation sector will have to purchase all its credits from the market. This full auctioning will commence in 2013; furthermore it is proposed that the amount of credits available on the market will be reduced by 1.74% annually (EU ETS). Although the model utilizes data from 2005 through 2008, the assumed market structure will be that off phase III. Motivated by the fact that most large scale capture plants won't be online till 2020. For instance, E.On Benelux Maasvlakte applied and received an EU sanctioned and partly subsidized 250MW demonstration post combustion capture plant to operate between 2015 and 2020 (CATO-2).

Presently, the CO_2 prices have stabilized under the EU ETS phase II– in contrast to the failure in phase I when a surplus of credits were on the market and subsequently the price crashed. As a result, the developed model will assume that the CO_2 prices will initially remain stable throughout a single 4 year model simulation run and vary between the runs. The reason for this approach is based on the premise that the model can present the user with an average operational income. The model uses 4 years to increase the accuracy of the operational income; for instance, 2005 has more peaks than 2007. Therefore, making use of 4 years gives a better outcome than just using one year.

Cost of Electricity and Avoided CO$_2$

From the general and time dependent inputs, in sections 3.2.1 & 3.2.2, these can be computed. In table 3.3 the COE and COA have been calculated with the use of the equations [EQ 3.1 & EQ 3.2]. In order to calculate €/MWh, the CAPEX and OPEX costs are converted into €/hr; also shown in table 3.3.

$$\text{Cost of Electricity (€/MWh)} = \text{COE} = \frac{\text{CAPEX} + \text{OPEX}}{\text{Net Electricity Output}}$$
[EQ 3.1]

$$\text{Cost of CO}_2 \text{ Avoided (€/ton)} = \frac{\text{COE}_{\text{Capture}} - \text{COE}_{\text{reference}}}{\text{CO}_2 \text{ Emission}_{\text{reference}} - \text{CO}_2 \text{ Emission}_{\text{capture}}}$$
[EQ 3.2]

Note, the cost of electricity is written in its general form; to calculate the COE of a given flexible option the specified CAPEX and OPEX as well as the correct net electricity produced needs to be applied. Also CO$_2$ emissions are measured in kg/MWh.

Table 3-3 Costs summarized

Costs	Without Capture	With Capture	Units
CAPEX	4,155.76	5,082.71	€/hr
OPEX	19,292.24	22,625.57	€/hr
Cost of Electricity (COE)	31.09	50.42	€/MWh
Cost of CO$_2$ Avoided (COA)	CO$_2$ Price / (C$_{\text{emit}}$/1000)[a]	29.37	€/MWh

[a] C$_{\text{emit}}$ measured in kg/MWh

Knowing the average price over data set period is €56.67 per MWh and the cost of electricity generation of the reference base case without capture is €31.09 per MWh, an annual profit can be expected. However, the costs for CO$_2$ aren't yet included in the calculation of the COE. Should the price of CO$_2$ break through the €25 mark and annual average prices similar to the 2005 -2008 period, then the commercial viability of a coal plant without PCC plant is in peril. Nonetheless, a higher CO$_2$ price will prompt investors to invest in capture to reduce the costs of CO$_2$ emissions to the atmosphere and remain a viable installation. Even though, this is a valid and interesting discussion, this research won't focus on the moment of investment instead focus on the performance of different mechanisms to elevate the economic costs of operating a capture plant. In the following sections, 3.3 and 3.4, the NO capture and 3 different FOMs models, as described technically in chapter 2, are described analytically. Moreover, the model constructions are revealed. First, the NO capture model is examined followed by the FOMs model.

3.3 No Capture – Business as Usual (BAU)

The function of this BAU model is as a comparative tool; i.e. the performance of a coal-fired plant with capture can be evaluated against it. In addition, this model will function as a warning; i.e. undertaking no action will result in reduced economic viability when expected CO$_2$ price rises happen.

The general and time dependent inputs will remain the same as described in section 3.2. Prior to expressing the equations, used to calculate the performance, it should be noted that the load profile as illustrated in section 2.1.2, is in effect for this and all other models. Equation 3.3, calculates the hourly operational performance (€/hr). Note that CAPEX costs are not included in the hourly operational

performance of this and other models; the decision for investment has been made and the focal point is operational performance.

$$
OP_{BAU} \ (\text{€/day}) = \begin{cases} [E(t)_p \cdot E_{net_{pc}} \cdot L_{low}] - [OPEX_{pc} + (C_{price} \cdot C_{emit_{pc}} \cdot E_{gross_{pc}} \cdot L_{low})] & \text{for } 1 \le t \le 7,\ t=24 \\ [E(t)_p \cdot E_{net_{pc}} \cdot L_{high}] - [OPEX_{pc} + (C_{price} \cdot C_{emit_{pc}} \cdot E_{gross_{pc}} \cdot L_{high})] & \text{for } \quad 8 \le t \le 23 \end{cases} \quad \text{[EQ 3.3]}
$$

Where, OP_{hr} = Operational Performance per hour (€/hr),

$E(t)$ = Electricity price at a given time (hr),

L_{low} & L_{high} = the load profile capacity factor of the PC power plant (%),

C_{price} = The price for CO_2 (€/kg)

$C_{emit(pc)}$ = The amount of emitted CO_2 to atmosphere without capture (Kg/MWh),

E_{net} & E_{gross} = Net & Gross electricity produced by the PC plant

t = Hours in a day (hr)

The CAPEX will be utilized later on to calculate the NPV of the flexible options. From the operational performance an annual operational income is calculated; this is then used to calculate the NPV of the flexible option. In the next section, the mathematical FOMs model constructs and the additional data required is presented.

3.3.1 Capture ONorOFF

Switching the capture plant ON or OFF depending on the current hourly electricity price and/or the price of CO_2 is the basis of this FOM and that of the partial capture model (3.4.2). For modeling purposes it has been assumed that switching between zero (OFF) and full (ON) load are instant from one hour to the next. In future research, the ramp-up and ramp-down speeds could be added. To calculate the hourly performance the input data from table 3.2 and 3.3 should be used. For clarity, the tables are combined in table 3.4 and the equation labels specified. Capture OFF includes the operational information for the PC power plant as well; Capture ON presents the additional costs to turn it on and its effects on other input parameters.

Table 3-4 Input values Capture ON or OFF

Input	*Capture OFF*	*Capture ON*	*Units*	*Label*
Net Electricity Output	754.30	549.60	MWe	$E_{net\,(*)}$
Gross Electricity Output	819	684	MWe	$E_{gross\,(*)}$
Operational Costs (OPEX)	169.00	29.20	M€/yr	$OPEX_{(*)}$
CO_2 Emitted	763.00	104.76	kg/MWh	$C_{emit(*)}$
Load Profile	N/A	N/A	%	$L_{low} = 0.41$ or $L_{high} = 1.0$
CO_2 Price	N/A	N/A	€/kg	C_{price}

* Denotes ON or OFF

To calculate the hourly operational performance of this FOM, equation 3.3 will be adapted to satisfy the requirements as set forth by this FOM. These requirements include, that when the capture plant is turned off, the operational costs of the capture plant are negligible. Although, in practice some O&M, labor and heating will remain; however, these costs are significantly lower than the other costs saved. In equation

3.4 the mathematical calculation for capture OFF is presented. In equation 2.5, the equation for capture ON is described. Later on the capture ON will act as a control to examine if the FOMs have a positive impact on the business case. The equations below are like those previously reported for one day (hour 1 till hour 24); this will be repeated for other days in the model.

$$OP_{off} \ (€/day) = \begin{cases} [E(t)_p \cdot E_{net_{off}} \cdot L_{low}] - [OPEX_{off} + (C_{price} \cdot C_{emit_{off}} \cdot E_{gross_{off}} \cdot L_{low})] & \text{for } 1 \le t \le 7, t=24 \\ [E(t)_p \cdot E_{net_{off}} \cdot L_{high}] - [OPEX_{off} + (C_{price} \cdot C_{emit_{off}} \cdot E_{gross_{off}} \cdot L_{high})] & \text{for } \quad 8 \le t \le 23 \end{cases}$$ [EQ 3.4]

$$OP_{on} \ (€/day) = \begin{cases} [E(t)_p \cdot E_{net_{on}} \cdot L_{low}] - [OPEX_{on} + (C_{price} \cdot C_{emit_{on}} \cdot E_{gross_{on}} \cdot L_{low})] & \text{for } 1 \le t \le 7, t=24 \\ [E(t)_p \cdot E_{net_{on}} \cdot L_{high}] - [OPEX_{on} + (C_{price} \cdot C_{emit_{on}} \cdot E_{gross_{on}} \cdot L_{high})] & \text{for } \quad 8 \le t \le 23 \end{cases}$$ [EQ 3.5]

From equations 3.4 and 3.5, one can see that when the capture is OFF an additional amount of electricity can be sold and operational costs are reduced. However, as $C_{emit(OFF)}$ is higher than when the capture is ON, the costs for CO_2 increase, dependent on its price. The modeled decision methods to have capture ONorOFF is based on a simple principle; if OP $_{off}$ > OP $_{on}$ then Capture OFF else Capture ON.

The turning point between ON or OFF occurs when operational performance for ON and OFF are equal. Knowing that only $E(t)_{p\ =}\ E_{price}$ and C_{price} are variables and the other values remain constant, the equation (2.6) can be rewritten:

$$x_{on} \cdot E_{price} - (OPEX_{on} + y_{on} \cdot C_{price}) = x_{off} \cdot E_{price} - (OPEX_{off} + y_{off} \cdot C_{price})$$ [EQ 3.6]

Where, $x = E_{net} * L_{low\ or\ high}$ (in the equation both sides are either at low or high load profile)

$y = C_{emit} * E_{gross} * L_{low\ or\ high}$

In order to know at which electricity price the capture is on or off, one should know the price of CO_2. Assuming that for short term periods that CO_2 price is stable, it can be seen as a constant. In other words, if the CO_2 price is known, one can calculate at which electricity price the capture plant is turned ON or OFF. In equation 3.7 the overall cost of CO_2 ($y_{on} * C_{price}$) is rewritten as C_{cost}; the subscript on or off denotes which type FOM is used.

$$E_{price} = \frac{(OPEX_{on} + C_{cost_{on}}) - (OPEX_{off} + C_{cost_{off}})}{x_{on} - x_{off}} = \frac{Expenses_{on} - Expenses_{off}}{Income_{on} - Income_{off}}$$ [EQ 2.7]

These equations are used in the model to calculate hourly performance for both capture ON and OFF and then a decision is made which option is more profitable (or has fewer losses). Therefore, as the CO_2 price gets higher, the capture plant will tend to switch the capture plant ON. However, the plant operator may still decide to keep the capture OFF if the electricity price is high enough to cover the higher CO_2 costs.

3.3.2 Partial Capture ONorOFF

Partial capture hourly performance can be calculated through the same construction as shown in 3.4.1. However, the inputs for the FOM are different. In this section the input data is extrapolated and adapted from the reference ASC 800MW base case with capture design (see figure 2.2). The coal plant remains the same, accordingly, for the costs and operational performance. In this FOM the capture plant will be scaled down in the design phase and a smaller capture capacity is installed. This means that the input data per

scale (80, 60 and 40 %) will be different. This section explores the changes to the following inputs: capital costs (CAPEX), operational costs (OPEX) and maximum CO_2 inlet flow.

To the knowledge of this author no exact figures have been published for a 640MW (80%), 480MW (60%) and 320MW (40%) post combustion plant. For this reason the author has extrapolated the necessary data from the reference 800MW ASC PC power plant. In this model amongst others, cooling water, equipment, steam demand, labor and manufacturing costs have been calculated. During the development/design of the reference base case the following values have been computed. These values are calculated from the size of the captured CO_2 (kton CO_2/yr). In table 3.5, the operational costs of different capture installations, according to the kton CO_2 /yr are presented. Note, the amount of CO_2 refers to the amount the capture plant can process. The 800MW base case capture plant captures around 4700 kton CO_2 per annum (marked as grey in table)

The total manufacturing costs according to the amount of CO_2/yr are larger than that reported OPEX costs of the reference base case with capture. However, this is caused by a different valuation approach; the base case assumes that the electricity, steam and cooling water costs are paid through an energy penalty. Therefore, the trend can still be utilized for extrapolating the operational costs of the scaled down versions of a capture plant. Before, analyzing the trend graphically, the extrapolation for the CAPEX costs are performed and demonstrated in table 3.6.

Table 3-5 Operational costs (OPEX) at various kton CO_2 / yr (TNO, 2009)

Size: kton CO_2/yr	10	50	100	200	400	800	1600	3200	*4700*	6000	Units
Electricity	0,02	0,09	0,18	0,36	0,71	1,39	2,81	5,59		10,60	M€/yr
Steam	0,09	0,46	0,93	1,85	3,70	7,30	14,68	29,29		54,82	M€/yr
Cooling Water	0,09	0,43	0,87	1,74	3,48	6,84	13,76	27,44		51,45	M€/yr
Rest (labor, etc)	2,11	2,44	2,71	3,26	4,12	5,67	8,50	15,83		27,89	M€/yr
Total Manufacturing costs	2,31	3,43	4,68	7,21	12,01	21,21	39,75	78,15		144,76	M€/yr
Adjusted to base case	**0,58**	**0,86**	**1,17**	**1,80**	**3,00**	**5,30**	**9,94**	**19,54**	**29,20**	**36,19**	**M€/yr**

Table 3-6 Capital Costs (CAPEX) at various kton CO_2/yr (TNO, 2009)

Size: kton CO_2/yr	10	50	100	200	400	800	1600	3200	*4700*	6000	Units
CAPEX costs	3,02	6,42	9,50	14,14	21,44	34,77	57,23	123,11		229,31	M€
Adjusted to base case	**3,63**	**7,71**	**11,40**	**16,97**	**25,73**	**41,72**	**68,67**	**147,73**	**203,00**	**275,18**	**M€**

The CAPEX costs as presented in table 3.6 are less deviating in comparison to the OPEX cost estimates. Nonetheless, figures diverge in the order of 20%. Again, the main reason for this can be explained by the different initial assumption in these models. Even though, the prices are a fraction higher in relation to the 800MW reference capture plant, the trend in up scaling isn't expected to change. Both, the OPEX and CAPEX costs are plotted against the captured amount of CO_2 per year; illustrated in figure 3.3. Note, OPEX costs are measured in M€/yr.
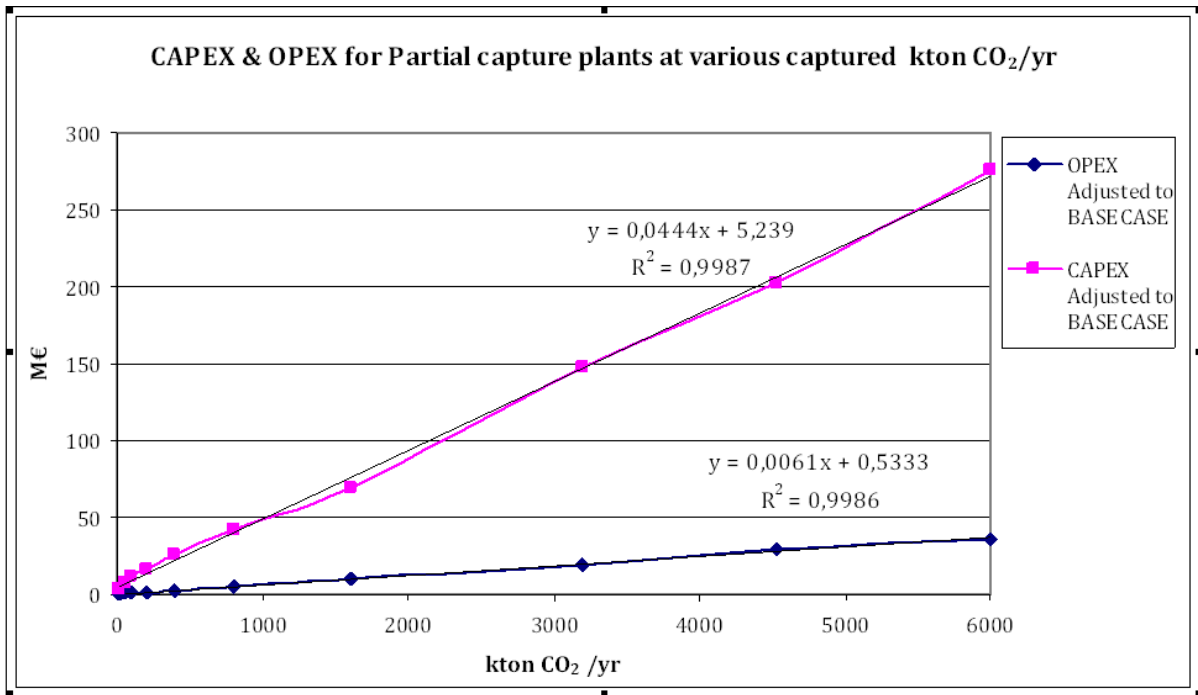
Figure 3-3 Graph that plots the amount of captured CO_2 against the cost (CAPEX & OPEX) to achieve these results

From the graph, two observations can be deducted. First, the CAPEX costs show clear economies of scale at kton CO_2 captured; from 10 to 800 kton CO_2/yr; i.e. the behavior is non-linear. Second, after 1600 kton CO_2/yr the trend becomes linear. The clarification for this behavior is found in the costs of equipment. At a low scale, equipment is enlarged; i.e. absorber columns are cylindrical and enlarging them increases materials in a non-linear manner. Whereas, larger scales require multiple equipments, therefore, costs are following a linear behavior. As a result, applying a linear regression on the curves can be assumed legitimate. Moreover, the linear regression has an high correlation coefficient of 0.99.

Using the linear equations for CAPEX and OPEX respectively, the CAPEX and OPEX costs for 80, 60 and 40% partial capture plants can be determined. The outcomes are presented in table 3.7; for comparative reasons the 100% plant is also shown.

Table 3-7 CAPEX & OPEX costs per Partial Capture size

Input	100% Capture	80% Capture	60% Capture	40% Capture	Units
Capital Costs (CAPEX)	203.00	166.53	126.20	85.87	M€
Operational Costs (OPEX)	29.20	22.65	17.12	11.59	M€/yr

Another input that changes is the maximum inlet of flue gas to the capture plant. Logic dictates that a smaller plant can process less CO_2 from the flue gas stream provided by the PC power plant. For the model it is assumed that the maximum flue gas inlet stream is relative to the size of the capture plant. Hence, 40% partial capture can only manage 40% of the 100% capture plant; these figures are posted in table 3.8. Besides the maximum inlet, the overall emitted CO_2 from the system (at high load profile) is shown. Additionally, the use of smaller capture plants ensures that more electricity is available to sell; therefore, the electricity output with the capture plant ON is also shown.

Table 3-8 CO$_2$ input data for partial capture plants

Input	100% Capture	80% Capture	60% Capture	40% Capture	Units
Max Inlet CO$_2$	763,00	610,40	457,80	305,20	Kg/MWh
Over all Emitted CO$_2$	104,76	236,41	368,06	499,70	Kg/MWh
Gross Electricity Output	684,00	711,00	738,00	765,00	MWe
Net Electricity Output	549,60	603,00	657,00	711,00	MWe

The overall emitted CO$_2$ is calculated with the following equation (3.8). The % sign denotes which partial capture value has to be used.

$$\text{Overall emitted CO}_2 \ (\text{Kg/MWh}) = (C_{emit} - \text{Inlet}_\%) + (\text{Inlet}_\% \cdot (1 - CAP_{rate})) \qquad \text{[EQ 3.8]}$$

Finally, partial capture will use the same model constructs as capture ONorOFF; the only difference is the initial input values. Equations 3.9 and 3.10 portray the formulae used to calculate the hourly performance of an 80% partial capture plant. Again the decision, if the capture should be turned ON or OFF is based on a simple principle; if OP$_{off}$ > OP$_{on}$ then Capture OFF else Capture ON.

$$OP_{off\,80} \ (\text{€/day}) = \begin{cases} [E(t)_p \cdot E_{net_{pc}} \cdot L_{low}] - [OPEX_{pc} + (C_{price} \cdot C_{emit_{pc}} \cdot E_{gross_{pc}} \cdot L_{low})] & \text{for } 1 \le t \le 7,\ t=24 \\ [E(t)_p \cdot E_{net_{pc}} \cdot L_{high}] - [OPEX_{pc} + (C_{price} \cdot C_{emit_{pc}} \cdot E_{gross_{pc}} \cdot L_{high})] & \text{for } \quad 8 \le t \le 23 \end{cases} \qquad \text{[EQ 3.9]}$$

$$OP_{on\,80} \ (\text{€/day}) = \begin{cases} [E(t)_p \cdot E_{net_{80}} \cdot L_{low}] - [OPEX_{80} + (C_{price} \cdot C_{emit_{80}} \cdot E_{gross_{80}} \cdot L_{low})] & \text{for } 1 \le t \le 7,\ t=24 \\ [E(t)_p \cdot E_{net_{80}} \cdot L_{high}] - [OPEX_{80} + (C_{price} \cdot C_{emit_{80}} \cdot E_{gross_{80}} \cdot L_{high})] & \text{for } \quad 8 \le t \le 23 \end{cases} \qquad \text{[EQ 3.10]}$$

Compared to equations 3.4 (capture off) and 3.5 (capture on), equations 3.9 and 3.10 vary slightly. The values of the above used constants (input values) are found in the following tables; For the OFF mode look in table 3.4, capture ON values can be found in tables 3.7 and 3.8. Note, that the subscript defines which value should be used; i.e. C$_{emit\,80}$ refers to the amount of CO$_2$ emitted to the atmosphere for a 80% partial capture plant. For the 60 and 40% capture plants the subscript is changed into 60 and 40 respectively.

From the equation one can see that turning the Capture plant ON will decrease the CO$_2$ costs and the net electricity output but at an increased OPEX cost (OPEX$_{pc}$ < OPEX$_{80}$); vis-à-vis turning the capture plant OFF removes the added OPEX costs of the capture plant and increase net electricity output but increase the CO$_2$ costs. As seen in section 3.3.1, the choice whether to run the capture plant is dependent on the electricity price and the price for CO$_2$.

3.3.3 Intermediate Storage

The last FOM is different in one significant other way; CO$_2$ prices do not influence the decision to momentarily halt stripping and compression duty. It will store absorption solvent at higher electricity demand and/or during peak electricity prices. Subsequently, extra stripping, of the stored solvent and compression of the CO$_2$, at times of lower prices and demand can be profitable. This FOM has two distinct actions; 1. a storage phase and 2. a extra stripping and compression phase -referred to as stripping phase. The storage phase will occur during the high load profile (from 7 am till 23pm) and the stripping phase shall occur at nightly low load (from 23pm till 7am). Another operational change, in relation to the other 2 FOMs is the fact that capture will always remain ON.

In chapter 2, it has been explained that this FOM will need additional equipment and land space. For the purpose of this model the land costs are not included; the main reason is that land price vary significantly between sites and land is an asset that could be resold at similar value. The equipment costs and dimensions will differ between the different sub-models of this FOM; 1, 2, 3, and 4 hours of storage. The longer the storage, the larger the storage tanks will have to be. Furthermore, the decision is made to use a two storage tank design; one tank to store "rich" solvent and the other for "lean" solvent.

In table 3.9, the relevant financial input data is presented for the intermediate storage FOM. These are the CAPEX costs. The energetic losses/gains are the same for are 4 sub-models; when stripping/compression is switched off (storage phase), 194.8 MWe extra electricity can be sold. Hence, during the stripping phase 194.8 MWe per hour are needed to strip the CO_2 from the "rich" solvent that was stored. Hourly operational costs of the stripping and absorption phase are different; During the absorption phase the OP_{absorp} = actual E_{price} * 194.8 MWe and for the stripping phase the OP_{strip} = COE_{is} * 198.4 MWe will be used. Where, COE_{is} the cost of electricity of a PC plant with capture and storage. The COE_{is} will vary slightly according to the amount of storage time. In table 3.9, the COE_{is} per storage time is also presented. A critical note – the costs of electricity is much higher than the average price for electricity during the low load period. If possible, the capture plant should use grid electricity instead when this is lower than the COE_{IS}.

Table 3-9 CAPEX costs intermediate Storage

Equipment	*1hr Storage*	*2hr Storage*	*3hr Storage*	*4hr Storage*	*Units*
Storage Tanks (AISI 304)	6.73	11.71	16.21	20.40	M€
Extra MEA	3.86	7.71	11.57	15.43	M€
Capital Investment (CAPEX)	**10.59**	**19.44**	**27.79**	**35.82**	**M€**
Cost of Electricity (COE)	51,1	51,6	52,1	52,7	€/MWh

To examine the operational performance, the OPEX costs are needed. However, instead of a financial value, as the CAPEX above in table 2.9, the operational costs are based upon the energy gains or losses. These gains are the same per hour of storage. Conversely, 4 hours of storage has a higher cost than 1 hour of storage; as it needs to spend more energy to strip the quantity of stored solvent. Nonetheless, storing for 4 hours at a high peak price can create greater benefits. The performance of the intermediate storage can be calculated as shown in equation 3.11. Note, the default equation is the same as capture ON – this is marked as OP_{on}.

$$OP_{IS} \ (\text{€/day}) = \begin{cases} [OP_{on} - (E_{extra} \cdot COE_{IS})S_{hrs} \ ] & \text{for } 1 \le t \le 7, \ t=24 \\ [OP_{on} + (E_{extra} \cdot E_{price})S_{hrs}] & \text{for} \quad 8 \le t \le 23 \end{cases} \qquad \text{[EQ 3.11]}$$

Where, E_{extra} (MWe) = The extra energy that is gained or lost while in storage or stripping phase,

S_{hrs} (hrs) = The hours that is being stored vis-à-vis stripped

From equation 3.11, it can be understood that this FOM will reduce operational performance during the low load profile and increase it during the high load profile. Yet, the actual performance will be dependent on the electricity price. Another important assumption, that is used for this FOM model, is that the lowest prices of electricity (during the low load profile) will be the time that the stripping phase will occur. In

contrast, the storage phase will occur at the highest electricity prices during the high load profile. Finally, intermediate storage will be able to switch in a moment between storing and normal default operation. This means that the storage hours do not have to be sequential. The advantage of this method is that intermediate storage can be operational for both daily price peaks.

3.4 Performance Indicators

Already mentioned several times, the main performance indicator for the FOMs is the operational income at a given CO_2 price. Also the COE and COA present valuable information to the user on the effectiveness of the FOM prior to simulation with the varying electricity and CO_2 prices. The model will use the average annual operational income and the capital costs to calculate a NPV for each FOM. Although, a NPV isn`t the best possible indicator for decision making it will suffice as a comparative value. The discount rate used for all the NPV's is 8%; the effect of the discount rate on the economic inputs will be shown in the sensitivity analysis in chapter 4. Furthermore, a cost benefit ratio is presented in order to define the value of each FOM from an investor perspective.

3.5 Synthesis

The aim of this chapter was to answer the sub research question: *how can the operational performance of the Flexible Operating Mechanism's (FOMS) be evaluated with the use of a model?* The suggested technique to evaluate the operational performance is to develop a model in Excel (3.1). The model will perform a retrospective techno-economic evaluation. This model makes use of inputs (section 3.2 and partly 3.3) that are constants, initial values and/or variables. The main variables are the price of electricity and the CO_2 price. Three flexible operating mechanism models have been developed:

1. Capture ON or OFF,
2. Partial Capture (80, 60 and 40% of capacity of the coal power plant),
3. Intermediate Storage (1, 2, 3 and 4 Hours)

These sub-models have been analyzed analytically and model equations given. Using this information the model is built and the next stage of the model can be reported. In the next chapter (4), the model will be verified and validated through the application of a sensitivity analysis. Furthermore, costs of electricity and cost of avoided CO_2 found in literature will be compared to those determined by the FOMs model. When the model has undergone a validation the results can be published and observations made.

Chapter 4 *Model Verification & Validation*

For any model verification and validation (V&V) are an essential part of the model development process; if the model is to be accepted and used to support decision making or present a coherent advice. This chapter aims to answer the following research question (C): *does the model satisfy all verification and validation tests?*

In section 4.1 the verification and in 4.2 the validation process is undertaken. In section 4.3, the combined conclusions of the V&V are discussed in the synthesis of this chapter.

4.1 Verification of the data

Verification is done to ensure that the model is programmed correctly, the algorithms used have been implemented correctly and that the model contains no bugs, errors and oversights. Verification is different from validation; in simple terms verification is the check of the mathematics and validation the check of the physics of the model. The V&V approach used has been described by the Los Alamos National Laboratory (LANL) published in 2004. In figure 4.1, the model development process is illustrated and shown where verification and validation processes occurs.
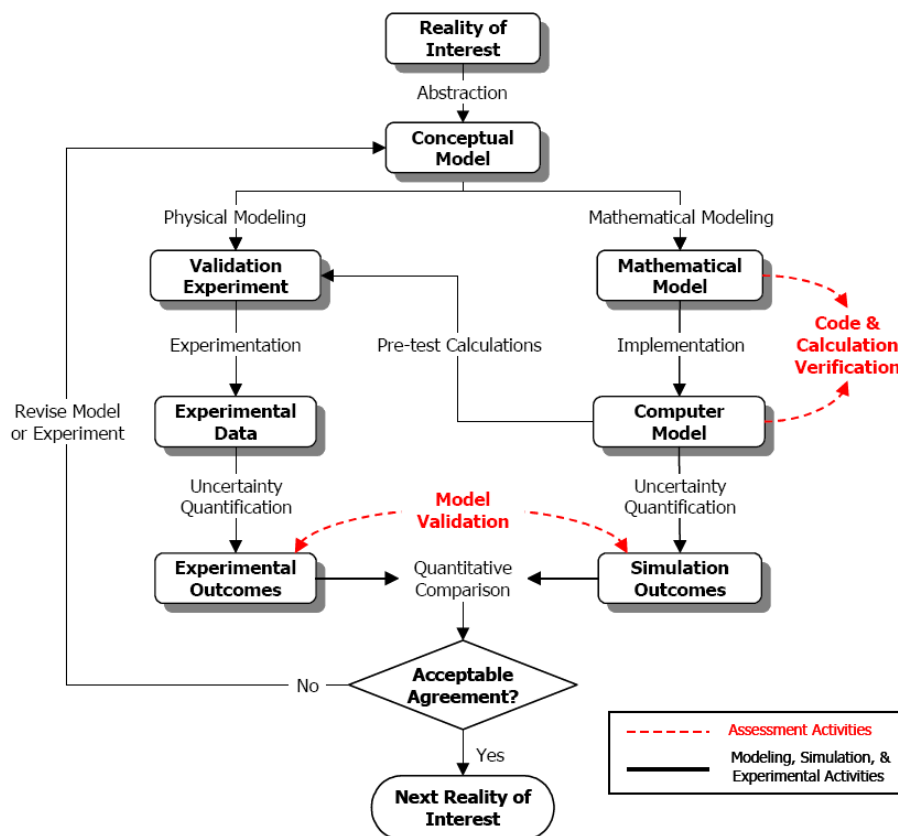
Figure 4-1 The model development, verification and validation process (LANL, 2004)

The conceptual model has been described in chapter 2 and the mathematical (or analytical model) has been described in chapter 3. The implementation of the mathematical model to a computer (excel) model is described in appendix B: model manual. In the next sections two verification tests are done; 4.1.1 Code verification and in section 4.1.2 the calculation verification

4.1.1 Code Verification

In chapter 3, several analytical equations to calculate the operational performance have been described. These analytical equations have been coded in excel. The main purpose of code verification is to ensure that the software is operating as intended. Hence, the focus is to identify and eliminate programming and implementation errors. A second goal is to verify the correctness of the numerical algorithms. In this section, a part of the models overall verification is presented through an example. However, this code verification has been implemented for all model constructs.

The mathematical equation (4.1) used to calculate the annual operational performance for the capture ON model is; (note - OP_{on} is in days, for annual multiply by 365 days/yr)

$$OP_{on} \; (\text{€/day}) = \begin{cases} [E(t)_{price} \cdot E_{net_{on}} \cdot L_{low}] - [OPEX_{on} + (C_{price} \cdot C_{emit_{on}} \cdot E_{gross_{on}} \cdot L_{low})] & \text{for } 1 \leq t \leq 7, \, t=24 \\ [E(t)_{price} \cdot E_{net_{on}} \cdot L_{high}] - [OPEX_{on} + (C_{price} \cdot C_{emit_{on}} \cdot E_{gross_{on}} \cdot L_{high})] & \text{for } \quad\;\; 8 \leq t \leq 23 \end{cases} \quad \text{[EQ 4.1]}$$

For the purpose of code verification the price for CO_2 is held constant and the average electricity price over the 4 year period is used. Furthermore, for simplicity the 100% capture plant will always be on.

For easily understood use, the excel model has named ranges; for instance, this means that the initial input value for CO_2 emitted by the capture plant is named: CO2_EMIT_100 (instead of excel cell D24). The "100" denotes that a 100% capture plant is connected to a coal plant. To convert the mathematical model to a computer model the following excel code is used. Important note – the calculation are done on a hourly basis in a single excel cell. In the model the costs for CO_2 are calculated in advance with the following code:

```
CO2_LOW_100 =(GROSS_PCC_100*LOAD_LOW)*(CO2_EMIT_100/1000)*PRICE_CO2
```

Where,   GROSS_PCC_100   = $E_{net\text{-}on}$
           LOAD_LOW   = L_{low}
           CO2_EMIT_100   = $C_{emit\text{-}on}$
           PRICE_CO2   = C_{price}

Using the cost for CO_2, during the low load profile, the hourly operational cost can be computed by the model. Similar to the mathematical model the load profile is different for two period during the day; a low (from 23pm till 7 am) and high (from 7am till 23pm). Again, an important distinction between the mathematical and computational model has to be made. Where, the mathematical equation can denote a given electricity price at a given time of the day, the excel model refers to the table of electricity prices on a separte spreadsheet; i.e. 'EP"!B4 refers to the first day and the first hour of that day (column B is hour 1, column C is hour 2, etc. – Row 4 is day 1, row 5 day 2, etc). The following excel code is used to calculate the hourly operational performance during the low load profile.

```
OPon (€/hr) = ('EP'!B4*NET_PCC_100*LOAD_LOW)-( OPEX_PCC_100+CO2_LOW_100)
```

Where,   'EP'!B4   = E_{price} at day 1 and hour 1 from the electricity price data set
           NET_PCC_100   = $E_{net\text{-}on}$
           LOAD_LOW   = L_{low}
           OPEX_PCC_100   = $OPEX_{on}$

In the previous paragraphs the excel coding for low load profile (from 23 pm till 7 am) are shown. For the other hours of the day the LOAD_LOW is changed to LOAD_HIGH. When translating the mathematical

model to the computer model, attention must be given to the correct notation. For each of the sub-models different, yet similar name ranges have been used; for instance NET_PCC_100 is different than NET_PCC_80. This is one of the simpler constructs because the capture is always on and the only changes within the spreadsheet are the load profiles and the cost for CO_2. However, a mistyping of an 80 or 60, a plus or a minus sign, can cause the code to fail, or worse produce wrong solutions.

For each of the FOMs sub-models the coding has been checked with the mathematical model as described in chapter 3. Some errors were detected initially, but have been rectified, and as such the model has passed the code verification test.

4.1.2 Calculation Verification

The purpose of calculation verification is to quantify the error of numerical simulation, and if possible, to provide an estimation of the numerical errors induced by the use of the model. For the FOMs model this means that the input values will have to be examined on their accuracy; or present the uncertainties within the results. Having uncertainties is integral of a techno-economic model; most inputs are estimations based on assumptions from other preceding models. For instance, the CAPEX and OPEX costs were derived from the reference base case. Although, this is a comprehensive model that includes various component, equipment and O&M costs, some of these have been approximated using percentages of total cost; for instance; maintenance is 2.5% of the total capital investment (TCI).

Calculation verification has also been called numerical error estimation. The numerical error estimation can be calculated using; Error = (Numerical result – Exact result). However, when the exact results aren't known, this type of verification become difficult to complete. Nonetheless, analyzing literature sources can provide insight into the uncertainties of the input values used. In chapter 2, already some of the input figures have been discussed and reasons given behind the approximations. In the subsequent paragraphs these are reiterated and tabled. In this field of research, the main result values used are 1) the cost of electricity and 2) the cost of CO_2 avoided for coal-fired power plants with post combustion capture. In table 4.1, these result values in the model are compared to those found in the available literature.

Table 4-1 COE and COA results of a Pulverized Coal power plant with Post Combustion Capture from literature

Costs	FOMs Model[a]	Gibbins et al[b]	Abu Zahra[c]	Van den Broek[d]	Units
Cost of Electricity (COE) no Capture	31	38	31	29	
Cost of Electricity (COE) /w Capture	50	54	57	43	€/MWh
Cost of CO_2 Avoided (COA)	29	34	39	23	€/Ton CO_2

[a] Calculations are performed using full time operations, 8760 hours of operation per year.
[b] Costs for capture include CO_2 compression to 110 bar but doesn't include storage or transport; also operational time is maximized. Furthermore a value of 7.5 c/kWh (dollars) was reported. €/$\$_{2009}$ was 1.4.
[c] Based upon 7500 operational hours
[d] Assumes that energy prices remain constant and that operational time is utilized to the maximum extent.

The FOMs model, is in part based upon the work done by Abu Zahra; the base case was developed at TNO separation technology were Abu Zahra co-developed the base case. The difference between the COE and COA as presented in table 4.1 can be found in the number of operational hours. The cost of COE and COA derived by Gibbens et al and Van den Broek are of the same order of magnitude. The cost of electricity is computed, using equation 3.1, shows that the summation of the CAPEX and OPEX costs should be divided

by the net electricity output. The figures published by Van den Broek (2007) vary for the CAPEX costs; Van den Broek 1850 €/kW vs. FOMs model 2200 €/kW. Hence, the overall cost of electricity and cost of CO_2 avoided is roughly 15 % lower and this can be related to the 15% lower CAPEX costs of the coal plant with capture.

All models, in general, have uncertainties within them. This section attempts to demonstrate that even with this inherent uncertainty, the values computed by the model are within acceptable estimation limits. On a critical note, these types of comparisons are suspect, because it is difficult to discern which, if either, code used is correct. Even if the solutions are the same, there is still no proof that the computed solutions are correct. However, in absence of sufficient non-verification evidence it does provide circumstantial evidence.

4.2 Model Validation

Validation assessment is the process of determining the degree of which a model is an accurate representation of the real world from the perspective of the intended uses of the model (LANL). To validate the model a sensitivity analysis will be preformed to analyze which parameters have a strong influence on the results of the model. In this section, the validation will be separated into two parts; 4.2.1 sensitivity analysis of the reference base case model and 4.2.2 sensitivity analysis of the FOMs model.

4.2.1 Sensitivity Analysis Reference Model

The FOMs model is a techno-economic model on a high operational level; it continues from a preciously built model. The foundation of the FOMs model is the TNO developed 800MW ASC pulverized coal plant base case. Therefore, in order to validate the data used for the FOMs model, the validation of this model should be presented. By reporting this validation process, more valid observations about the results can be given. In table 4.2, the effect of fuel price and interest rate on the COE and COA are shown.

Table 4-2 Effect of interest rate and Fuel price on the COE and COA (Abu Zahra, 2009)

Fuel Price €/GJ	Interest Rate	COE no Capture €/MWh	COE with Capture €/MWh	Cost of Avoided CO_2 €/ton CO_2
1.2	0.08	28	53	37
1.6	0.08	31	57	39
3.2	0.08	44	76	48
1.6	0.04	27	48	33
1.6	0.08	31	57	39
1.6	0.12	37	68	47

From the sensitivity analysis, table 4.2, performed by Abu Zahra in 2009, it was found that the fuel price and the interest rate will have a significant impact on the cost of electricity and the cost of avoided CO_2. As the price of fuel (coal) rise the COE and COA increase too. The COE for coal plants with capture is in the range of 53-76 €/MWh and without 28-44 €/MWh; this represents on average a 70-90% increase in COE. Obviously, this increase can be accounted to the additional energy required to capture the CO_2. Therefore the COE has a strong dependence on the price of fuel. Relating these findings to the FOMs model, the calculated price of COE is dependent on the values (CAPEX & OPEX) gained from the base case; i.e. also

dependent on fuel price and interest rate. The marked row in the table, are the figures used in the FOMs model.

Abu Zahra continues to explain that the cost of avoided CO_2 (COA) shows a balanced increase with the increase of the fuel price; typically a doubling of the fuel price leads to a 23% increase in the COA. Again, relating these finding to the FOMs model implies that the calculated cost of avoided CO_2 in the FOMs model are dependent on the fuel price and the interest rate. This validation is focused on the economic parameters CAPEX and OPEX; therefore for the subsequent paragraph, the sensitivity analysis for the FOMs model will be done assuming that the economic factors have passed the initial validation test.

4.2.2 Sensitivity Analysis FOMs Model

The sensitivity analysis for the FOMs model will focus on those parameters that influence the simulation outcomes. The main calculated outcome of the FOMs model is: yearly operational income. The variables that have a strong influence on the outcome are; the price of CO_2 and the electricity prices. This section will describe how strong these factors alter the outcome. The FOMs that will be used for the sensitivity analysis are:

1. No capture
2. Capture ON 100%
3. Capture ONorOFF 100%
4. Capture 100% with 1 hours intermediate Storage

Even though there are more FOM models, they are variations on those listed above. Hence, results from the sensitivity analysis on these 4 will reflect on the other sub models.

The premise for this sensitivity analysis is that if the 4 listed sub-models are validated more significant observations can be made during the result phase of this research. The methodology of this sensitivity analysis is to vary the electricity price factor (E_f) to increase the average electricity price of the data set and examine the impact on the outcomes of the model. Furthermore, while varying electricity prices the operational performance (M€/yr) will be studied at different CO_2 prices. The results of this sensitivity analysis are shown graphically in figure 4.2 and the calculated increases per incremental change of E_{price} and CO_2 price in table 4.3.

From figure 4.2, it can be seen that no capture, 100% capture ON and intermediate storage (1Hr) are linear relations. However, Capture ONorOFF has a non linear relationship when CO_2 prices rise; this is logical as higher CO_2 prices increase the need for capture (i.e. Capture ON). However, the change in the electricity price factor (difference between the curves) remains linear. In table 4.3, the difference between electricity price and operational outcome is shown. Note, the price for CO_2 is kept at €30 per ton. If the chosen CO_2 price is too low, Capture ONorOFF model will present similar figures as No capture; i.e. more economical to keep capture OFF at low CO_2 prices.

From table 4.3, it can be read that a change in the average electricity price (€/MWh) has an influence on the operational income. For instance, for every €/MWh rise in the average electricity price the 100% Capture ONorOFF model will increase the operational income by 19%.
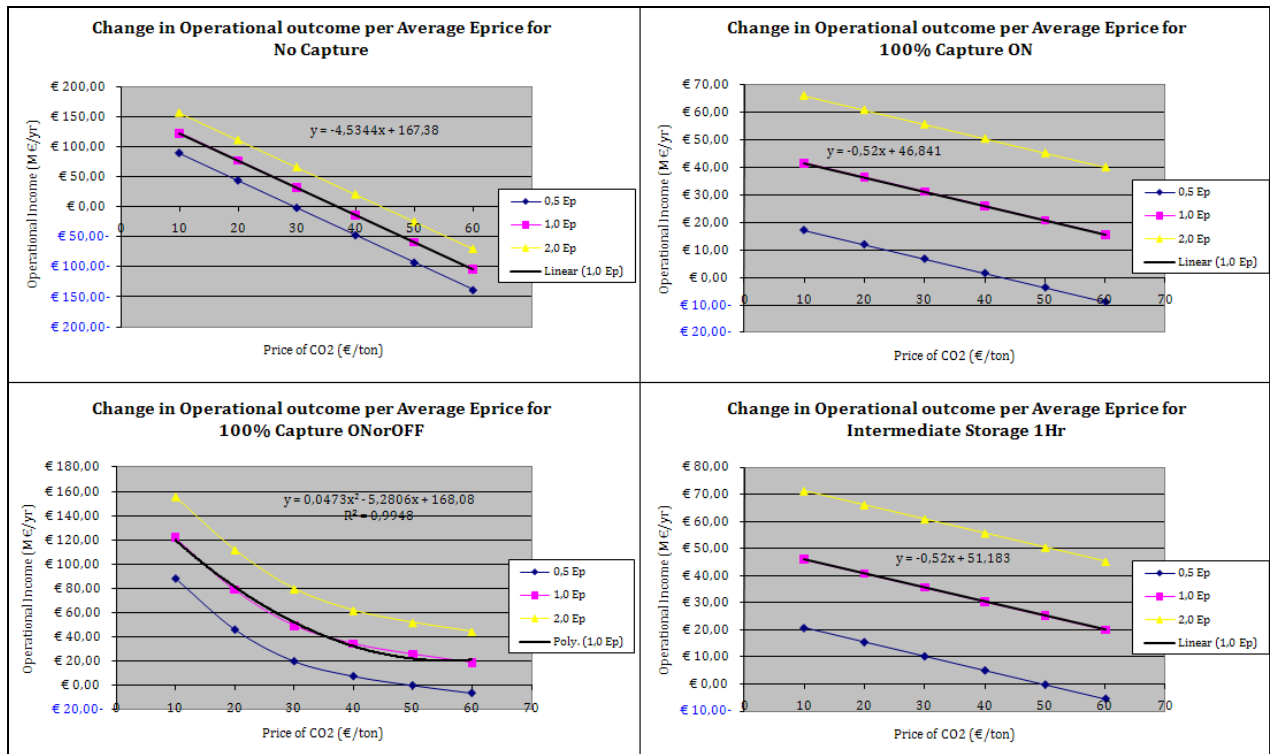
Figure 4-2 Change in operational income at varying Electricity and CO₂ prices

The other models range between 18% and 24%. The NO capture model is influenced the least by the electricity prices as it has a lower operational cost. Finally, it can be stated that the operational income is strongly dependant on the average price of electricity.

Table 4-3 Change in operational income whilst varying average electricity price

AVG Electricity Price	NO Capture	100% Capture ON	100% Capture ONorOFF	Intermediate Storage 1Hr
51.0 €/MWh (90%)	€ 2,30-	€ 6,72	€ 19,89	€ 10,25
56.6 €/MWh (100%)	€ 31,34	€ 31,24	€ 49,47	€ 35,58
62.4 €/MWh (110%)	€ 64,99	€ 55,76	€ 79,78	€ 60,91
Δ AVG E / OP income	18%	24%	19%	23%

4.3 Synthesis

The goal of this chapter was to answer the following research question: *does the model satisfy all verification and validation tests?* To answer this question, verification and validation test on the model were undertaken. No model can ever be a completely verified or valid; however, it can pass the tests to increase confidence in its ability to perform its intended function. From the V&V test it can be said that the models outputs for cost of electricity and cost of avoided CO_2 are in the ranges of other models. Furthermore, the sensitivity analysis has shown that the economic parameters are dependent on the fuel prices and that the FOMs simulation results are greatly influenced by the price for CO_2 and electricity. Concluding, the model has passed the V&V tests but the dependencies will have to be remembered in order to provide clear result observations. In the next chapter the results of the model are presented.

Chapter 5 *Model Results & Scenario's*

In this chapter the results of the model are published. Initially, in section 5.1, the operational performance of each FOM model will be presented and discussed. Using the operational performance a NPV analysis of each FOM is undertaken and presented in section 5.2. The NPV analysis, using the capital costs and operational performance at the given electricity prices (data set 2005-2008), will show that the FOM models have a negative NPV. Furthermore, a cost benefit ratio (CBR) is presented to give investors an insight in the value of the FOMs as potential investment options.

Naturally, the current electricity price dataset is non-representative of future prices. Therefore, part of this chapter's goal is to answer the following research question: *How do different scenarios impact the results of the model and the business case?* The scenarios consist of possible changes in CO_2 and electricity prices. The implemented scenarios in the model are expressed in section 5.3. The results of these are interpreted in section 5.4. Finally, a synthesis of this chapter can be found in section 5.5

5.1 Annual Operational Performance

The annual operational performance (M€/yr) is an indicator how the proposed system (capture with a FOM) performs economically on an operational level for a given year. The model calculates the hourly gains or losses (hourly performance) and adds them together to give the total 4 year performance. To get the annual operational performance, this value is divided by the number of years that the simulation runs; 4 years. Each FOM has its own characteristics and underlying equations but the general method to calculate the operational performance remains the same; i.e. Income for electricity sales – (operational expenses + CO_2 costs).

In the subsequent sections, the various operational results are discussed; NO Capture (5.1.1), Capture ON (5.1.2), Capture ONorOFF (5.1.3) and intermediate storage (5.1.4). NO Capture, on an operational level, has the same result as Capture OFF for all scales of partial capture. This is logical as operational costs when the capture plant is turned off are the same as a coal plant with no capture. To compare the performance of the FOMs, a capture ON model is presented. The FOMs aim is to increase the operational income compared to leaving the capture plant always on. In addition, each sub-section within section 5.1 presents the operational status of the FOM at a given CO_2 price.

5.1.1 NO Capture – Capture OFF

The annual operational performance of a coal plant without a capture plants is the same as a coal plant with capture that is turned off; even though the capture plant will have an operational costs that includes maintenance costs, for the purpose of this model these costs are neglected. However, capture OFF will have a lower NPV as capital costs are higher. In figure 5.1, a graphical representation of the annual operational performance of a coal plant without a capture plant is shown. The graph depicts the income at a given CO_2 price. Knowing the COE (31 €/MWh) and the COA (19.66 €/MWh @ CO_2 price of 15 €/ton) and the average electricity price of the data set (56.6 €/MWh) it is clear that a higher CO_2 price will impact the overall annual operational performance. From the graph, figure 5.1, it is found that at a CO_2 price around 36-37 €/ton yields a negative operation income; i.e. an operational loss is incurred.
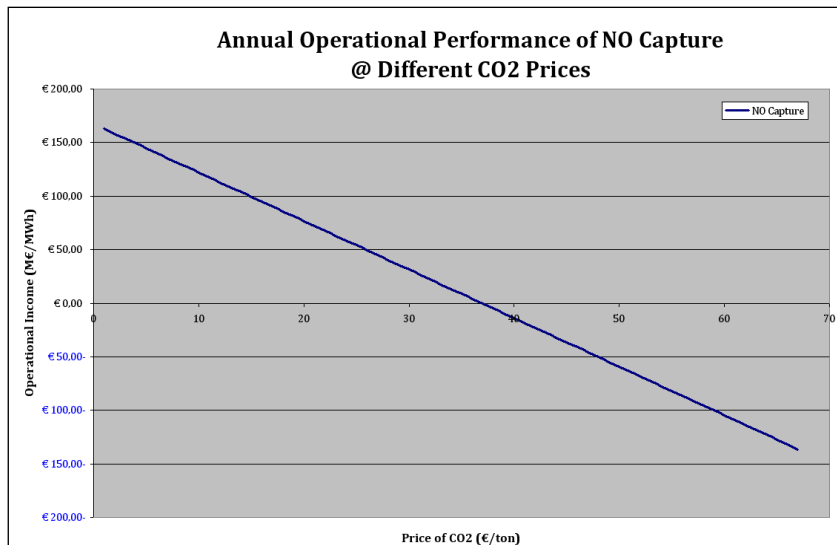
Figure 5-1 Annual operational performance of a coal plant without capture at different prices for CO₂

Another, logical result is that the change in of operational performance is linear and negative; i.e. for every 1 €/ton CO2 increase then operational performance approximately decreases by 4.5 M€/yr. This change in operational performance of a coal plant without capture can be compared in section 5.1.2 with a coal plant with capture.

5.1.2 Capture ON

In contract, to the previous section, capture ON will have a higher operational cost than NO capture and thus have lower initial operational performance. However, after a certain CO_2 price the capture ON will outperform the coal plant without capture. In graph, figure 5.2, after approximately 31€/ton CO_2 the capture ON will yield a higher (non-negative) operational income.
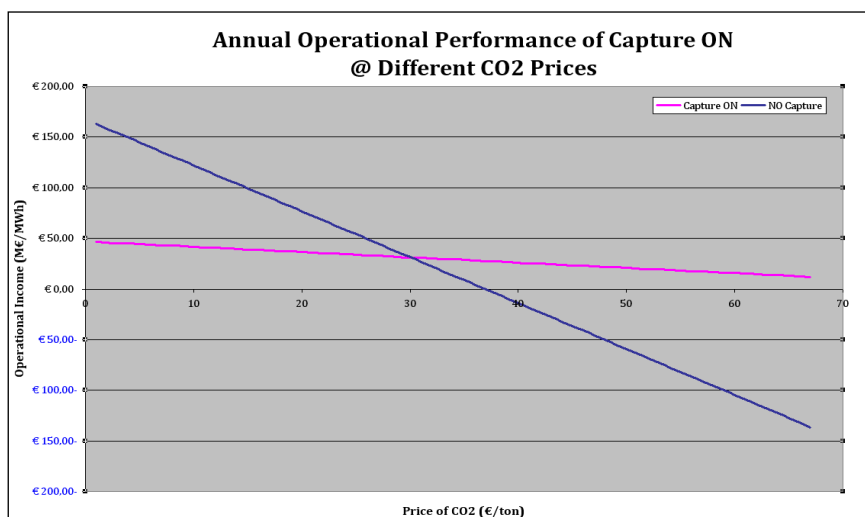

Figure 5-2 Annual Operational Performance of a coal plant with and without capture

The rate of change of the operation performance, for capture ON, is less negative than NO capture. Where, a coal plant will lose 4.5 M€/yr for every 1€ rise of the CO2 price; Capture ON will lose 0.5 M€/yr. The two (5.1.1 and 5.1.2) sections deal with the operational performance without any FOMs. The next two sections present how applying these mechanisms the operational performance can be improved.

5.1.3 Capture ONorOFF

Deciding whether or not to turn the capture plant ON or OFF will depend on the electricity and CO_2 price. The FOM capture ONorOFF will attempt to maximize the advantages of capture ON and capture OFF (NO capture). Initially, the performances of a 100% capture plant are compared to that of a coal plant with and without capture; figure 5.3.
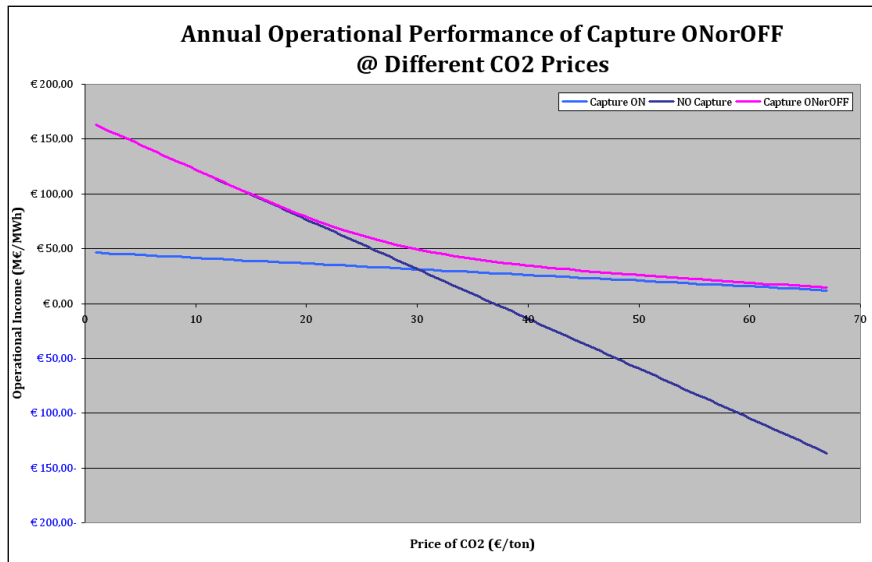

Figure 5-3 Annual Operational Performance with FOM capture ONorOFF
Compared to coal plant with and without capture

By turning the capture ONorOFF at a predefined electricity price the capture plant is able to improve its operational income. It will remain above the two other curves because it will use the best performance option. At low CO_2 prices the operational state of the capture plant is very low (capture OFF), however the operational condition increases with the CO_2 price. Nonetheless, by switching the capture plant on or off out performs both a coal plant with (always on) and without capture. At the point where with and without capture intersects (€30/ton CO_2) the added operational income from the FOM maximized at 20M€/yr. When CO_2 prices are lower or higher than this intersection point then the added operational income is smaller.

Another FOM, using the same ONorOFF principle, is partial capture; installing a smaller capacity of capture, leads to lower investment and operational costs. However, at higher prices of CO_2 it will be less economically efficient. As expected, a smaller capacity capture plant will have a quicker operational status (higher frequency of ON at low CO_2 prices). In figure 5.4 consist of three graphs, these are the resulting operational performance for 80, 60 and 40% partial capture plants; however, the operational performance between the partial capture FOMs are hard to visualize. Thus, two graphs are added to provide a closer look at the changes in behavior of the FOMs.

The parts of the graph that are of interest are at the ranges of CO_2 prices where the FOMs differ in their operational performance. Between 11 and 22 €/ton CO_2, each of the partial capture start to gain a higher operational performance in relation to 100% capture ONorOFF. The reason that 40% capture can start earlier then other scales with the capture of CO_2 is that its lower operational costs allows it to turn on at lower CO_2 prices.
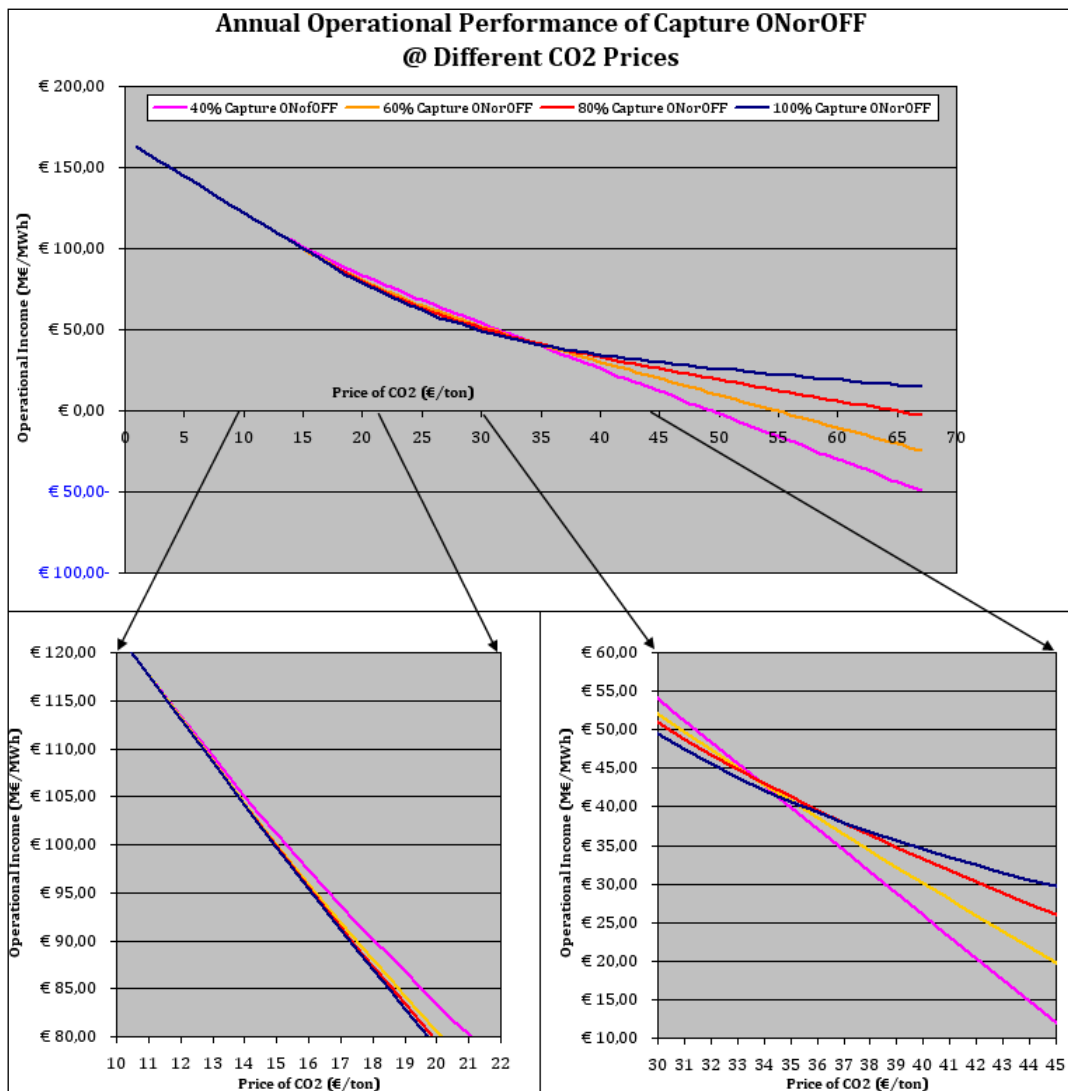
Figure 5-4 Operational Performance of 100, 80, 60 and 40% Capture ONorOFF

Between 33 and 37 €/ton CO_2 the partial capture plants start to have less operational performance in relation to 100% capture ONorOFF. The agreement for this behavior is the reduced capability to capture the increasingly expensive emissions.

Another observation is that at higher prices of CO_2 the effect on operational performance is stronger; where 100% capture will be able to remove 86% (capture rate) of the CO_2 from the coal plants flue gas while 40% capture, at the same capture rate, removes 34%. Furthermore, the price of CO_2 when operational performance is maximized is lower for each partial capture FOM. In table 5.1, a summary is presented of the partial capture FOMs and their maximized operational income and change in operational performance (only for % Capture ON) when prices increase by a €/ton CO_2. Logically, these max operational performances are near the cost of avoided CO_2 per FOM.

Table 5-1 Maximized operational performance and change in operational performance

Capture with FOM	Max Operational Performance @ CO_2 price - ONorOFF	Operational Income @ CO_2 price = 1€/ton	Change in Operational Performance per €/ton CO_2 increase – Only ON
100% Capture	30	46.3	-0.5
80% Capture	27	76.0	-4.8
60% Capture	24	104.9	-7.9
40% Capture	18	133.1	-11.2

Table 5.1, provides valuable information about the effectiveness of a capture plant at a given scale. Even though, 40% capture is able to reach its maximized operational performance at a lower CO_2 price, it sacrifices in robustness; i.e. it is very sensitive to changes in CO_2 prices. However, 40% capture ON in relation to 100% capture ON will have a have a higher operational performance at lower CO_2 prices. Vis-à-vis, 80% capture will have an elevated operational performance at higher CO_2 prices than 60% capture.

Interesting to note 40% capture has a relatively larger operational income impact than 60 and 80% capture. Since, 40% capture will utilize its full operational capacity quicker than the others. Figure 5.5 demonstrates this phenomenon; the curves present the percentage of capture ON at a given CO_2 price.
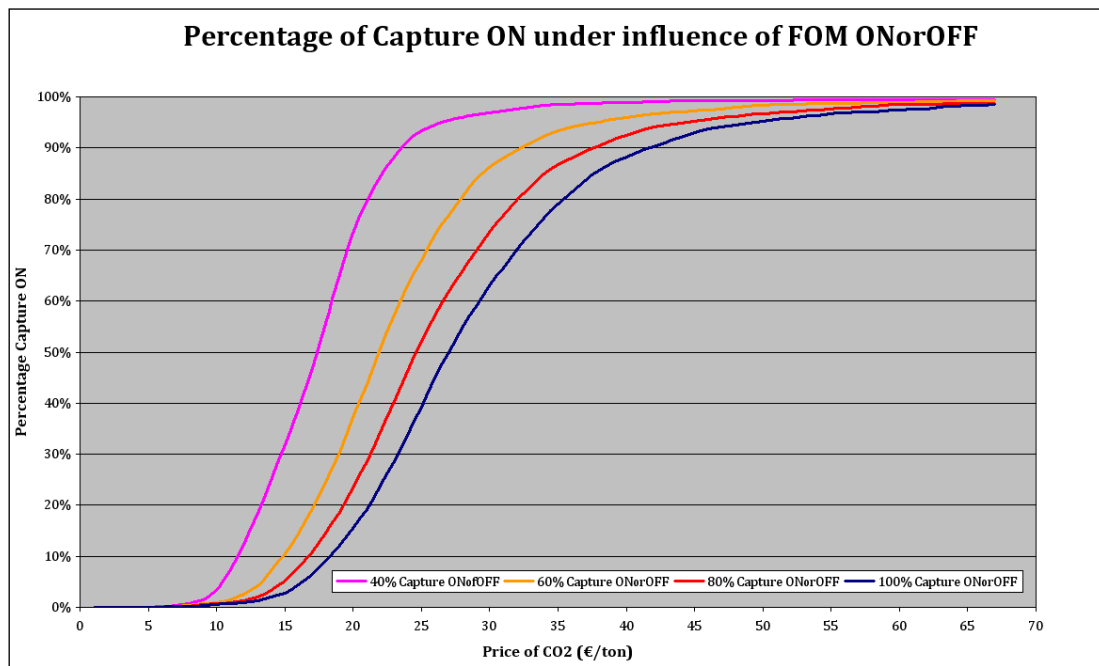

Figure 5-5 Operational status of the Partial capture FOMs at a CO_2 price

To calculate the value of the capture plant, the number of operational capture hours can be used. For instance, at 20 €/ton CO_2 a 40% capture plant operates at 73%. A 40% capture plant has a capital cost of approx 86 M€ and an expected lifetime of 25 years. Assuming that capital costs for the capture plant will only be attributed to actual operational hours. Without discounting the CAPEX costs over its lifetime, but assuming equal annual payments, a back of envelop calculation shows that a 40% capture plant costs roughly 540€/operational hour. In table 5.2 this example is calculated for 60, 80 and 100% capture at 20 €/ton CO_2.

Table 5-2 Actual CAPEX cost per operational hour per FOM

Parameter	Capture 100%	Capture 80%	Capture 60%	Capture 40%	Units
CAPEX capture plant	203	167	126	86	M€
CAPEX / Hr	926	760	576	392	€/hr
% Operational	15	23	37	73	%
Actual CAPEX / OP$_{hr}$	6180	3310	1560	540	€/Operational Hr

The aim of this example is to demonstrate that for an investor the not only the operational performance income is important but also the effectiveness of the investment. Even though, this example doesn't reflect the amount of CO_2 captured (Annual CO_2 costs 100% = 12 M€/yr and 40% = 15 M€/yr), it does provide a reasonable estimate of the value of capture plant. For fullness the costs of CO_2 for Capture ON for each coal fired plant with a partial capture plant are shown in figure 5.6.
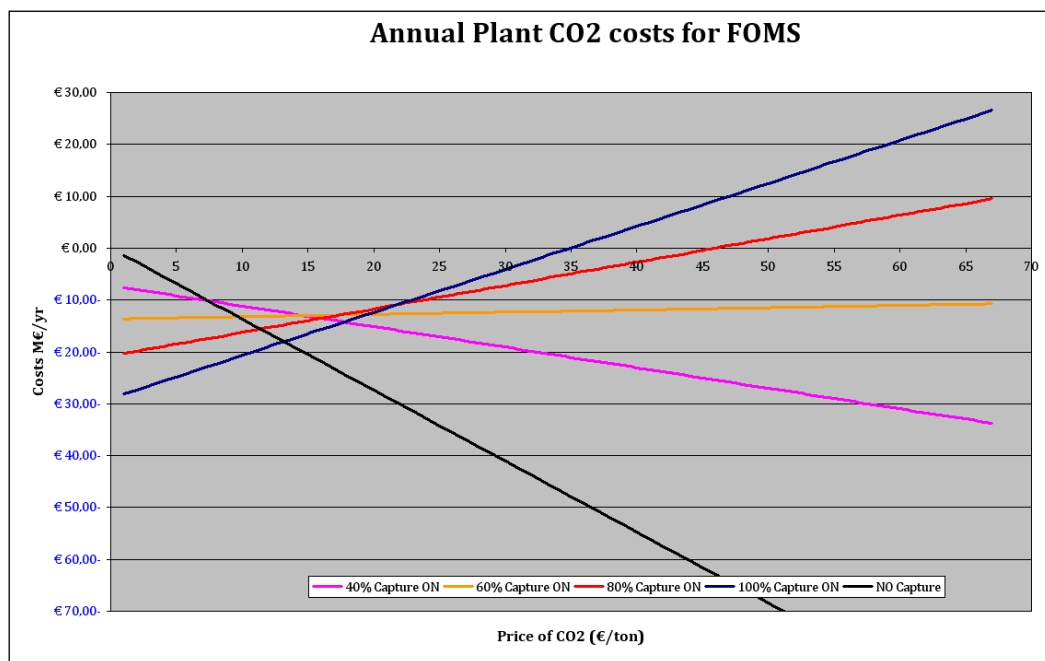

Figure 5-6 Costs of CO_2 annually for various FOMs

The costs of CO_2 will initially be lower for the coal fired plant without capture. It will only have to pay the low CO_2 price where as the coal fired plant with capture already has extra incurred operational costs. However, around 14 €/ton CO_2 all partial capture plants will have reduced CO_2 costs. 100% and 80% (at 35 and 45 €/ton CO_2 respectively) capture plants will return a negative value for the cost (a profit).

These operational benefits for the capture ONorOFF model are promising but they will have to be related to the capital investment costs. The reduction of the operational costs is only half of the equation; the savings in operational costs, or increase in operational income, should cover the investment expenses. In section 5.2, NPV's for the various FOMs will be calculated at different CO_2 prices.

5.1.4 Intermediate Storage

The last FOM that has been proposed is intermediate storage. Intermediate storage is not directly dependent on the price of CO_2; however it is dependent on the price of electricity. The model assumes that intermediate storage will occur every day; in reality the plant's operator could use storage at any time if

the electricity price warrants its. Nonetheless, the decision has been made to store everyday for each intermediate sub-model. Intermediate storage will be connected to a 100% capture plant and as such will be compared to the performance of one without storage.

In figure 5.7, the operational performance of intermediate storage is compared with that of a coal fired plant with capture always ON.
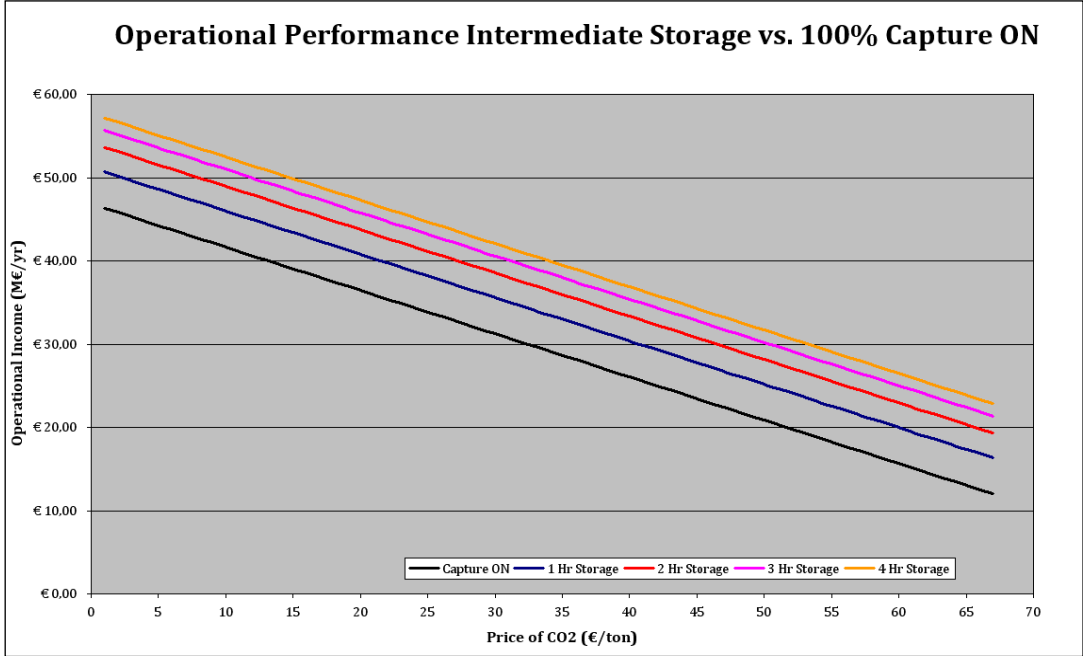

Figure 5-7 The operational performance of a coal plant with capture always on vs. same plant with different storage times

As previously stated, the intermediate storage FOM is affected indirectly by the price of CO_2 because of its interaction with the capture plant. However, the price of CO_2 doesn't determine its decision to enter a absorption or stripping phase. Figure 5.7 does illustrate that intermediate storage increases the operational income by a fixed amount. Relatively, 1 hour of storage increase the income more than 2 hours and so forth; 1 hour storage selects the highest electricity price of that day and starts storing en 2 hour storage the first two highest, etc. This explains in part the reason for the decreasing added performance in relation to a shorter storage time. For the current electricity prices intermediate storage adds an additional operational income ranging from 4.3 to 10.8 M€/yr (1hr to 4hrs).

In figure 5.8, the decreasing added operational income is shown. Note – the value for 4 hours is the difference between the performance of 4 storage hours minus that of 3 hours. This decreasing added income suggests that an optimum could be calculated. An utility graph could represent this as a parabola curve with the optimum; however, the model assumes that no more than 4 hours can be captured. Although, earlier assumption has stated that more the 4 hours of storage time would require an increase in capture capacity it is reasonable to assume that using the additional costs to improve the capacity of the capture plant, extra stripping and compression pumps against the extra revenues gained can be optimized. However, although interesting for future work, it is outside the scope of this thesis.
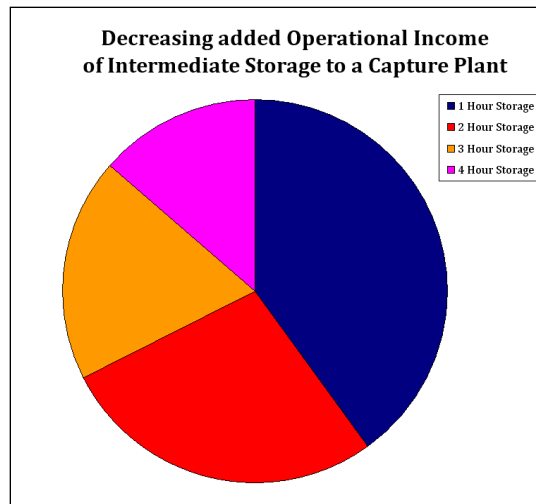
Figure 5-8 Adding additional hours of storage time decrease the added operational income per extra hour of storage

Having established that intermediate storage can add extra revenues to a capture plant, it should be examined at which times the absorption and stripping phases occur. In figure 5.9 the curve of average operation performance per hour for a capture ON is shown and compared to the operation performance curves of the 4 different intermediate storage FOMs.
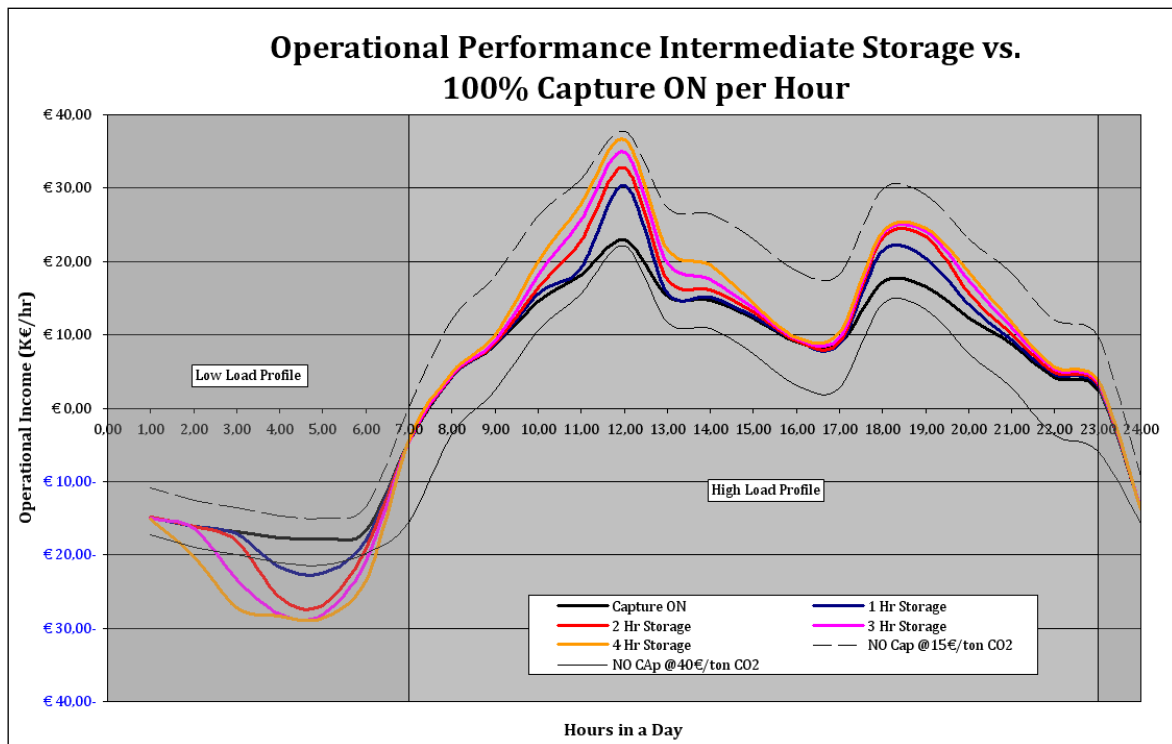
Figure 5-9 Increase revenues during high load profile, decrease revenue during low load profile

During the low load profile, when electricity prices are lowest, extra stripping and compression is done to remove the CO_2 from the absorption solvent. The absorption phase occurs during the high load profile when energy demand is greatest and was peak prices take place. The intermediate storage and capture on curves are created with the CO_2 price of 40 €/ton. The curve presents additional information; two average

hourly operation performance curves for a coal plant without capture. At 15 €/ton CO_2 the coal plant without capture performs better than the capture plant. However, at 40 €/ton CO_2 the capture plant out performs the plant without capture. Interesting is to point out that the capture plant with 4 hours of storage, at a price of 40 €/ton CO_2, almost reaches the coal plants performance at the peak time (noon).

In conclusion, intermediate storage can add significant revenues to a capture plant. Although not modeled, it is expected that intermediate storage could also be added to partial capture plants and boost income. Furthermore, intermediate storage has the added advantage that no CO_2 is emitted to the atmosphere. This could proof important if future changes occur in emissions regulations and/or markets.

5.2 Cost-Benefit Analysis

The analysis of the operational performance of the various plant/capture configurations and FOMs suggest that it could improve the business case of a coal-fired power plant with post combustion capture. However, to fully understand the FOMs capability to improve the business case the capital costs (CAPEX) will have to be included. Using the FOMs operational performance and the CAPEX involved for each type a Cost-benefit analysis can be done. To analyze all models on equal footing a Net Present Value (NPV) can be calculated. The NPV is calculated by discounting all the annual costs and income back to the present value and summating these. The goal of a NPV is to indicate whether or not an investment adds value to a firm. If the NPV is positive at a reasonable discount rate then the investment maybe accepted. However, if it is negative then the investment will only subtract value from the firm and should be avoided. When the NPV is 0 then the decision to invest may rest on other criteria. To ensure a valid comparison between the FOMs, each NPV will have the same discount rate (8%). The choice to use this discount rate was based on the reference model developed by TNO. In this model the choice was made to use an 8% discount rate.

Within the FOMs model a NPV is created to examine the NPV's at different CO_2 prices. The focus of this thesis is to examine if the FOMs can improve the business case; the emphasis should be on "improve". In section 5.2.1, where the NPV for a coal-fired plant with and without capture are presented, shows that the business case (NPV) is a negative one. Nonetheless, the FOMs can still improve the business case of a coal plant with capture; reducing the negative value of the NPV. This is done in section 5.2.2. The NPV doesn`t provide the full picture for an investor; therefore a Cost Benefit Ratio is calculated. This can be found in section 5.2.3.

5.2.1 NPV's coal plant without and with Capture

The NPV of a coal fired plant without capture shows that it is sensitive to the changes of CO_2 prices. The NPV is created using the CAPEX and OPEX costs derived by the reference base case and the operational performance from the FOMs model. This means that the operational income is based on the electricity prices and at a given CO_2 price. From figure 5.1, it is demonstrated that the operational income decreases as CO_2 prices increase. When keeping the electricity price data set fixed for each run with a different CO_2 price the total annual benefit can be calculated. Note, the initial investment will be done in year 0. Although, in practice this investment could be spread over a few years; i.e. during construction time (3-4 years).
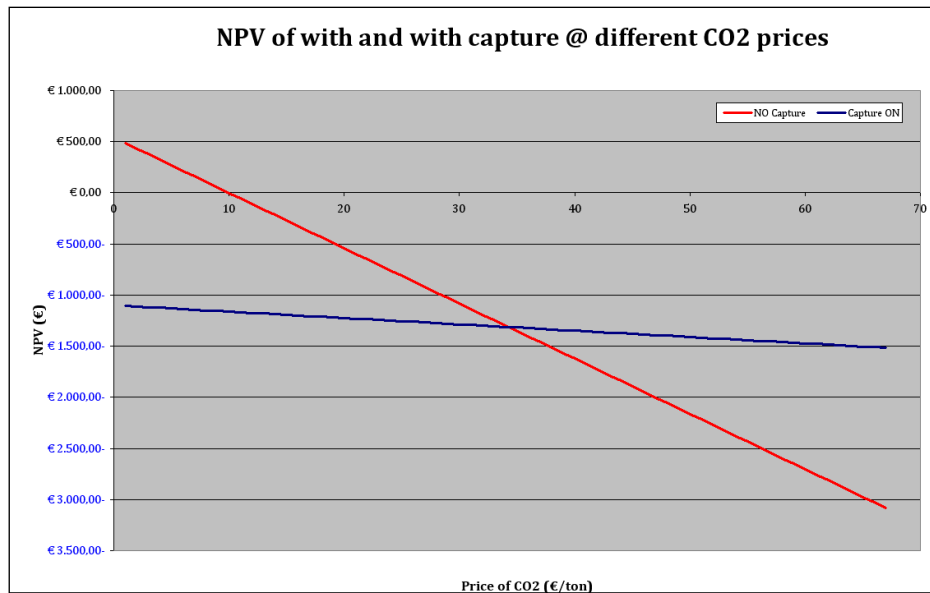
Figure 5-10 NPV at a given CO₂ price for without and with capture

In figure 5.10, the NPV of a capture plant without capture and with capture are calculated; the inputs for the NPV's per CO_2 prices are the same for the capital costs; €1456 M€ and 1659 M€ respectively for without and with capture. Operational income will depend on the price of CO_2 as calculated by the model. For reference, the specific operational income for without and with capture at a given CO_2 price are shown in figure 5.2.

Realizing, that the average electricity price = 56.6 €/MWH and that the cost of electricity for a coal-fired plant without capture is 31 €/MWh and at 10€/ton CO_2 the Cost of avoided CO_2 is 17 €/MWh, the NPV is as expected negative. Another factor that contributes to the negativity of the NPV is the cost of CO_2. Prior to 2013, in the European Union, energy producing companies have received free credits and this is reflected in the electricity prices. The model assumes the post 2013 environment, where energy producers will have to purchase its credits on a full auctioning market. On the other hand, a coal plant with capture has a even lower initial NPV. However, once the CO_2 price is high enough to cover the added investment (at 34-35 €/ton CO_2) the NPV of a coal-fired plant with capture is higher than its counterpart without capture.

The models initial assumed operating environment will mean that the coal-fired power plant with capture is a negative one. However, the value of the NPV can still play an important role; i.e. the comparison with the NPV's of the different FOMs. In this capacity the NPV will act as a performance indicator and present a value of the FOMs. Furthermore, the NPV values of the FOMs offer the opportunity to rate the FOMs in relation with one another. In the next section, 5.2.2, these will be presented.

5.2.2 NPV's Coal Plant with Capture applying FOMs

A coal-fired plant with capture applying FOMs is shown (section 5.1) to boost operational revenues but at a certain investment cost. By discounting future benefits (operational income) and costs (capital investment) the present value can be attained. Similar as done in figure 5.10, the capture plants applying the ONorOFF FOMs are compared to a coal plant with capture always on (control). A comparison to a coal plant without capture is also illustrated on the graph (dashed line).
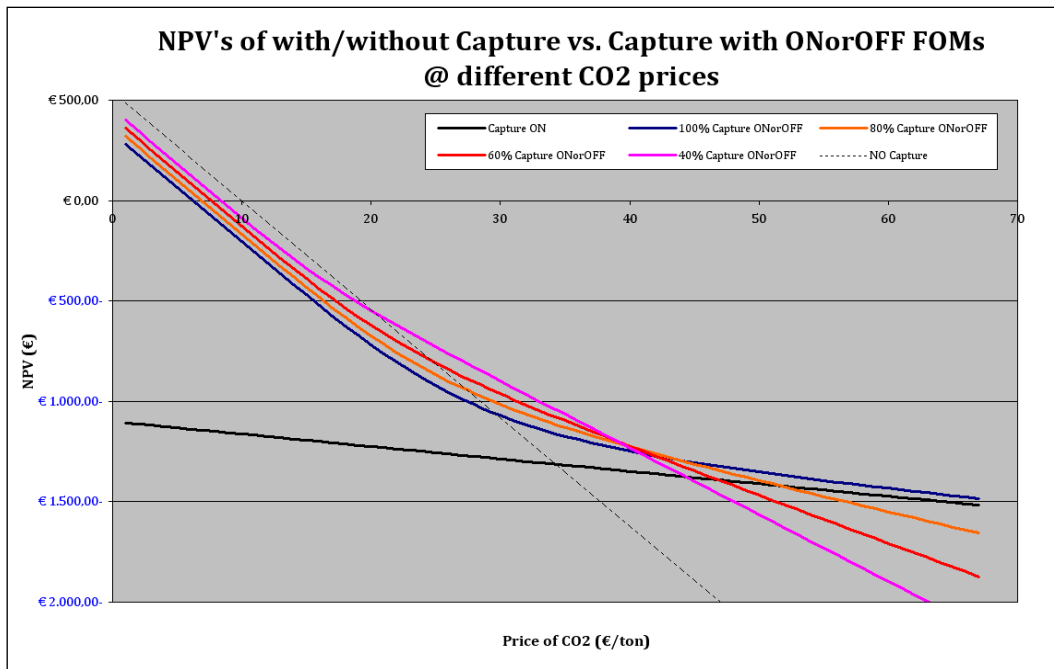
Figure 5-11 Calculated NPV's at different CO$_2$ prices for Capture ONorOFF FOMs compared to NPV Capture ON

From figure 5.11 the main observation is that the initial NPV's of a capture with the ONorOFF FOM are positive; a contract to capture ON without any FOMs. This can be explained through the decision to keep the capture plant OFF at low CO$_2$ prices. The difference between the FOMs and the coal plant without capture is the lower starting NPV; investments for the FOMs reduce its NPV. When the CO$_2$ price rises (20-30 €/ton CO$_2$) the FOMs have a relative better NPV than a plant without capture. As established in 5.2.1, the coal plant with capture becomes less negative than without capture, at 34 €/ton CO$_2$, the FOMs achieve this feet at lower CO$_2$ prices. Respectively, for 40% to 100% capture ONorOFF FOMs are achieving a higher NPV at 20, 25, 28 and 30 €/ton CO$_2$. This doesn't mean that a 40% capture plant is better than a 100% plant; when CO$_2$ prices rise above 40 €/ton 40% capture plants will value less than larger scale plants. At this stage, the incurred CO$_2$ costs aren't reduced by the smaller capture plant anymore. Therefore, the decision to either invest in a larger or smaller scale is dependent on the expected trend of CO$_2$ prices and electricity prices. Nevertheless, the observation that incorporating the ONorOFF FOM can prove beneficial for the coal plant with capture business case can be made.

Another FOM developed was underlined intermediate storage; from the operational performance it was found that this action can boost income by a significant amount at any CO$_2$ price. The increase amount is dependent on the electricity prices; more specifically, the occurrence of low prices during the lowest demand and peak prices at largest demand. In figure 5.12, the NPV's of the intermediate storage are compared to a coal plant with and without capture. Re-emphasizing that the intermediate storage is connected to 100% capture plant.
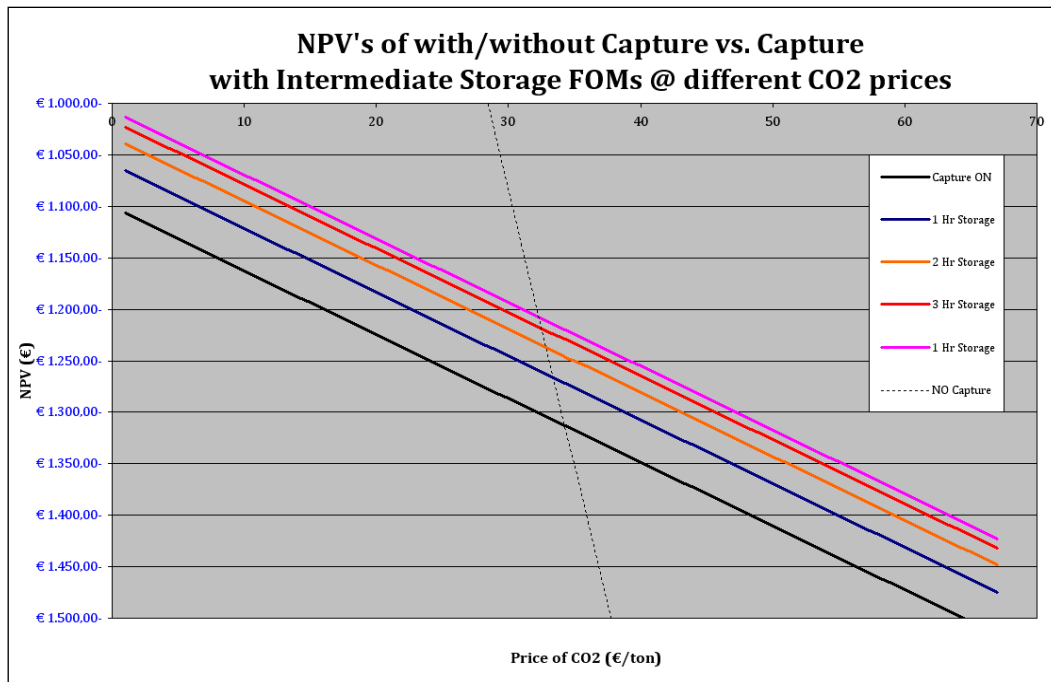
Figure 5-12 NPV's of 100% capture plant with intermediate storage (1 through 4 hrs) compared to coal plants with/without capture

Less impressive than the achievement in improving the business case caused by the ONorOFF FOM, nonetheless, an improvement vs. a plant with capture can be achieved at any CO_2 price. Whereas, the smaller partial capture plants under achieve in relation to a capture ON plant at higher CO_2 prices, intermediate storage will keep adding to the value of the capture plant. Remembering, that intermediate storage doesn't increase emissions of CO_2 this option could be more valuable if emission regulations are intensified or market changes that artificially inflate the price for emissions. These, non economic decision criteria will be explained in section 5.4. From the NPV analysis several key remarks can me made:

- The capability to switch between full and zero capture load has an significant benefit to the NPV for a coal plant with capture,
- Initially building a smaller capacity will yield an improved business case, however at higher CO_2 prices this advantage is lost to larger capture plant scales and even a full scale that is always ON.
- Intermediate Storage adds to the value of a capture plant at any CO_2 price.

5.2.3 Limitations of NPV analysis & Cost Benefit Ratio

Even though the NPV can demonstrate the value of a project it does have limitations. The most mentioned is that it takes no account for opportunity costs; i.e. the gained value when waiting to invest. For the NPV's analysis, using the FOMs model, the electricity prices were those provided for the 2005-2008 period and kept the same for each published NPV. In a future operational environment, conditions could be more favorable to invest. For instance, when energy producers have to purchase all their credits from a full auctioning market it is expected that the electricity prices will be higher than those reported during 2005-2008.

To give an investor better insights on the performance of the FOMs the NPV's can be used to calculate the cost benefit ratio (CBR). The CBR is a comparison of present value of an investment decision or project with its initial costs. The CBR is calculated by dividing the NPV by the initial investment costs (CAPEX). Should the ratio be greater than 1 it indicates that the project is a viable one; for every invested euro more than a euro is gained. From, this point forward the CBR will be used to compare the different FOMs. In figure 5.13, the CBR of the different FOMs are presented at the initial input values. Interesting is to note that none of the FOMs have a value that is above 1; also a coal plant without capture would find it hard to justify its investment under the current conditions. However, this can be explained by the assumptions; 'real' world coal plants would also supply bilaterally to large clients at fixed prices that do create value. The assumption that all electricity from the coal plant must be sold on the APX skews the data. Nonetheless, having applied the same assumption to the models it can be compared.
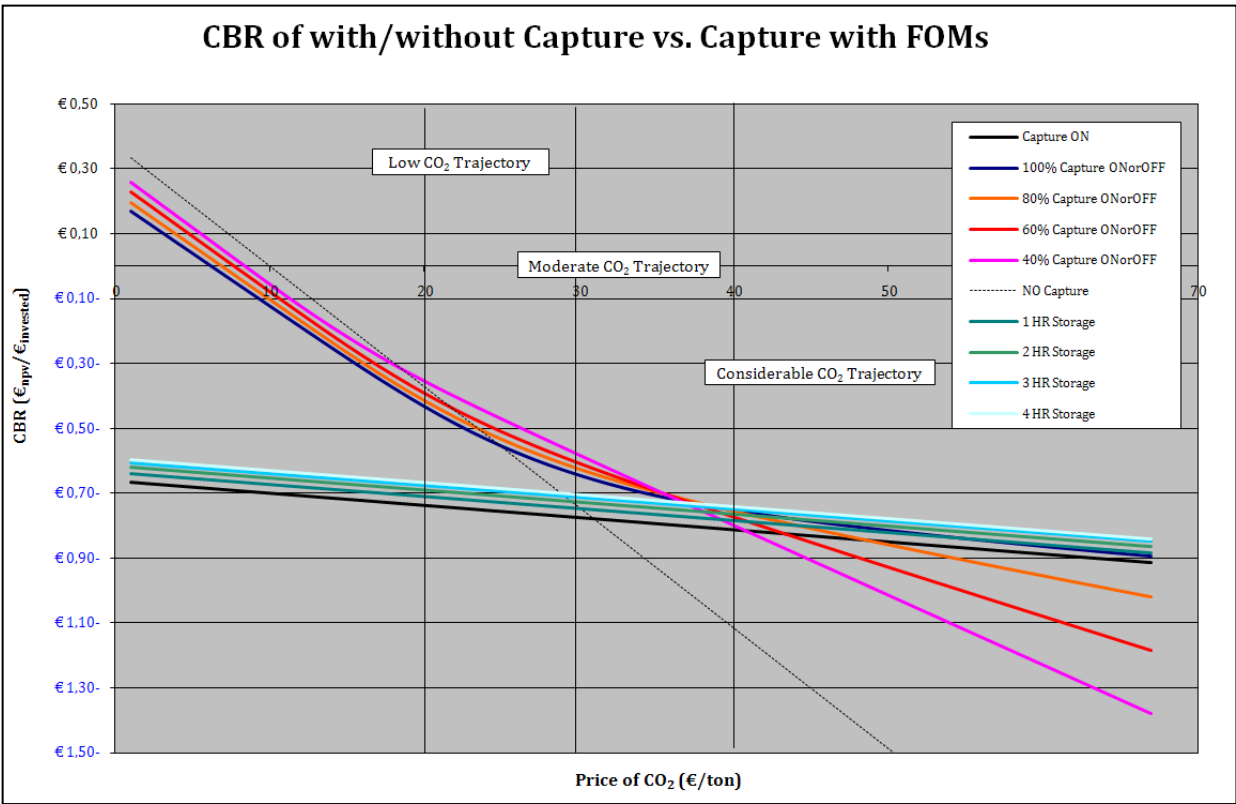
Figure 5-13 CBR of capture plant with FOMs compared to capture ON and NO capture

In the next section, 5.3, scenarios are established based on electricity price trajectories; low, moderate and considerable. As shown above a CBR will be used to compare the FOMs.

5.3 Scenarios: Future Performance

In the first part of this chapter, the results of the model are calculated using a fixed electricity price data set. Furthermore, the price for CO_2 was assumed flat throughout the lifetime of the coal plant without & with capture. In reality, these would evolve over time and have varying trends. In this section different scenarios are described that would influence the outcome of the model. The scenario is described as an

environment with a given electricity price and change in CO_2 prices. However, the likelihood that a scenario will occur is left to the reader.

The main uncertainty for investors in capture technology is the evolution of CO_2 and electricity prices. Shown by the model, these two parameters can break or make a business case. The models capability to add trends over a lifetime of a coal-fired plant with capture is limited. However, the model is able to show at which CO_2 prices and average electricity price the business case is viable or not (or which configuration less negative). Therefore, the aim of the scenarios is to examine how the FOMs would perform at a certain the electricity price whilst altering the CO_2 price. In 2015-2020 there are still large scale pilot demonstrations being completed. It is expected that the first commercial large scale post combustion capture plants won't be operational before 2020. Therefore, the period of interest in which coal-fired plants will need to invest will be between 2020 and 2030.

The scenarios will be based on the policy scenarios developed by Horn and Diekmann (2007) and fuel price predictions made by BMU (2008). Horn and Diekmann suggest three electricity price trajectories and three possible evolutions of CO_2 prices; each called low, moderate or considerable. In table 5.3 the different possible electricity price trajectories are provided. In the table, a brief reason for this possible rise in electricity price is argued.

Table 5-3 Scenario description at different electricity price trajectories

E- Price Trajectory	Argument for a trajectory
Very low: +20% €/MWh	A small increase in the price of coal, value used in the model is 3€/GJ is expected and as such also influences the electricity price. Electricity prices rise with economic growth & demand. CO_2 prices have a small impact on the 'doing' of business.
Moderate: +40% €/MWh	The prices of fossil fuels have increase by 'moderate' amount and according to the IEA world energy outlook (2007) this can be attributed to the shortages in oil and gas. Even though the price for coal has only slightly increased. The rises in the other energy sources impact the electricity market moderately.
Considerable: +80% €/MWh	The price for coal is increase more than three fold. This considerable trajectory is slightly above the high price predications of the IEA, 2007. The prices for coal have risen due to increase use of coal on a global scale and demand is high for a resource that is being used faster than it can be mined.

The prices of coal that have been suggested, as well as other energy sources, are shown in figure 5.14 (left). The energy source that is of interest for the coal-fired plant is 'hard coal'. On average the fuel prices range between 3.5 – 7.0 €$_{2005}$/GJ for the period 2020 and 2030. Relating this back to the sensitivity analysis performed by Abu Zahra (2009) in chapter 4 we learn that a doubling in fuel prices has a 70-90% increase in the cost of electricity (€/MWh) and a 20-25% increase on the cost of CO_2 avoided. Assuming that the average electricity price > COE, then the prices used for the very low, moderate and considerable are estimated to be approximately: 70, 80 and 100 €$_{2011}$/MWh.
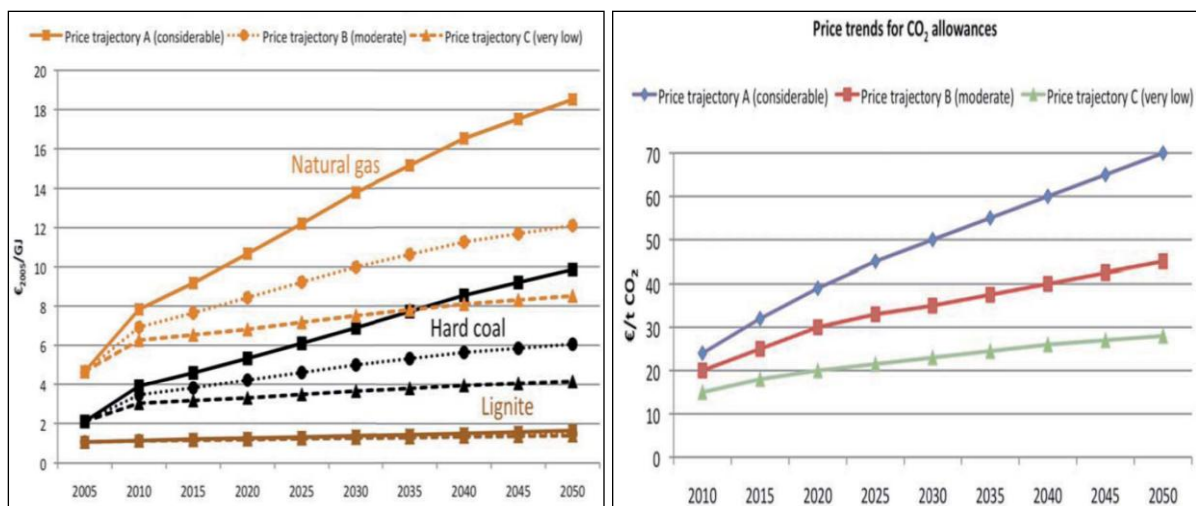
Figure 5-14 (left) predicated prices of fuels and (BMU, 2008), (right) predicated CO_2 price trends in real €$_{2005}$

In addition, to fuel prices, the CO_2 prices should also be discussed. Again, low, moderate and considerable increases of the CO_2 price trajectories are discussed. In table 5.4, a plausible reasoning is given for this trend.

Table 5-4 Scenario descriptions at different CO_2 price trajectories between 2020 till 2050 (Horn & Diekmann)

C- Price Trajectory	Argument for a trajectory
Very Low: 15-28 €/ton CO_2	The EU ETS is functioning less adequate then intended. Credits are being bought on a imperfect market were surplus credits are abound. Furthermore, monitoring of emissions is lacking and thus reduces the affectivity of the market as a whole. An annual reduction of credits isn't influencing the price.
Moderate: 20-40 €/ton CO_2	The EU ETS is functioning and the prices for CO_2 have reached those predicated it should reach. The market is operating such that demand only slightly outweighs supply of credits; Annual reductions in credits creates and moderate and steady increase of CO_2 prices.
Considerable: 24-70 €/ton CO_2	The EU ETS is functioning better than predicted. The price of CO2 has increased much higher than initially expected or predicted. The demand for credits is higher than the supply. Driving prices increasingly higher.

The three electricity price estimates for the very low, moderate and considerate trajectories are changed in the model and a new performance of the FOMs is calculated. The results that will be of most value are the NPV calculations. These include both the operational income and capital costs to value the FOMs under different electricity prices. These results are presented in the next section, 5.4.

5.4 Scenario Results

By changing the average electricity price of the 2005-2008 dataset, but keeping its characteristics, a new simulation run is done. The performance during the 2020-2030 periods is of particular interest; this will be the presumed period in which investment in capture will take place. According to figure 5.14 (right) the average price of CO_2 during the 2020-2030 decade is 20, 30 and 45 €2005/ton CO_2 for respectively low, moderate and considerable CO_2 trajectories. In section 5.4.1, scenario low trajectory will be evaluated for

each of the possible CO_2 price trajectories and discussed. In sections 5.4.2 and 5.4.3 the moderate and considerable trajectories of the average electricity price is discussed.

5.4.1 Low Electricity Price Trajectory

With an average electricity price of 70 €$_{2008}$/MWh, it is only 20% higher than the 2005-2008 average. However, the implications can be seen in figure 5.15. On the graph additional lines have been drawn to indicate where the CO_2 trajectory will be at in 2025 according to Hors and Diekmann. During the low trajectory of CO_2 prices both the NPV for a plant without capture and a plant with 100% capture using the FOM ONorOFF score approximately the same. It is also interesting to note that, compared to the 2005-2008 period, the intermediate storage competes with the ONorOFF FOM as least negative business case in the considerable CO_2 trajectory. However, for both the low and moderate CO_2 trajectory a 40% ONorOFF capture plant is the best scoring capture business case. Still, at a 20% higher electricity price the NPV's are negative, and consequently a negative CBR, for the moderate and considerable CO_2 trajectories.

Figure 5-15 CBR's of a coal plant with & without capture and using FOMs at a average electricity price of 70€/MWh

5.4.2 Moderate Electricity Price Trajectory

During the moderate electricity price trajectory the average price is 80 €$_{2008}$/MWh. This is 40% higher than the electricity prices used in the initial testing stage. The results from the recalculated CBR's are illustrated in figure 5.16. It should be noted that the scales are different from figure 5.15 in order to show the increased CBR values. Figure 5.16, demonstrates that, in relation to figure 5.15, a higher average price has a strong influence on the business case for a coal plant with capture.

The behavior between the FOMs remains the same; i.e. 4 hours of storage will always provide a higher CBR then 3 hours and so on. Furthermore, 40% capture ONorOFF plant starts out better but at a

certain CO_2 price it is overtaken by larger scale capture plants. However, the higher the electricity price the higher the CO_2 price needs to be for a larger capture plant to be more effective than a smaller one. Finally, the 40% capture plant with a ONorOFF FOM outperformed other FOMs at the moderate and considerable trajectories. At the lowest average electricity price (low trajectory) a coal plant without capture still has a better business case than any capture plant applying any FOM. However, other decision criteria, such as environmental and public perception, could add enough external value to the project to invest in capture.
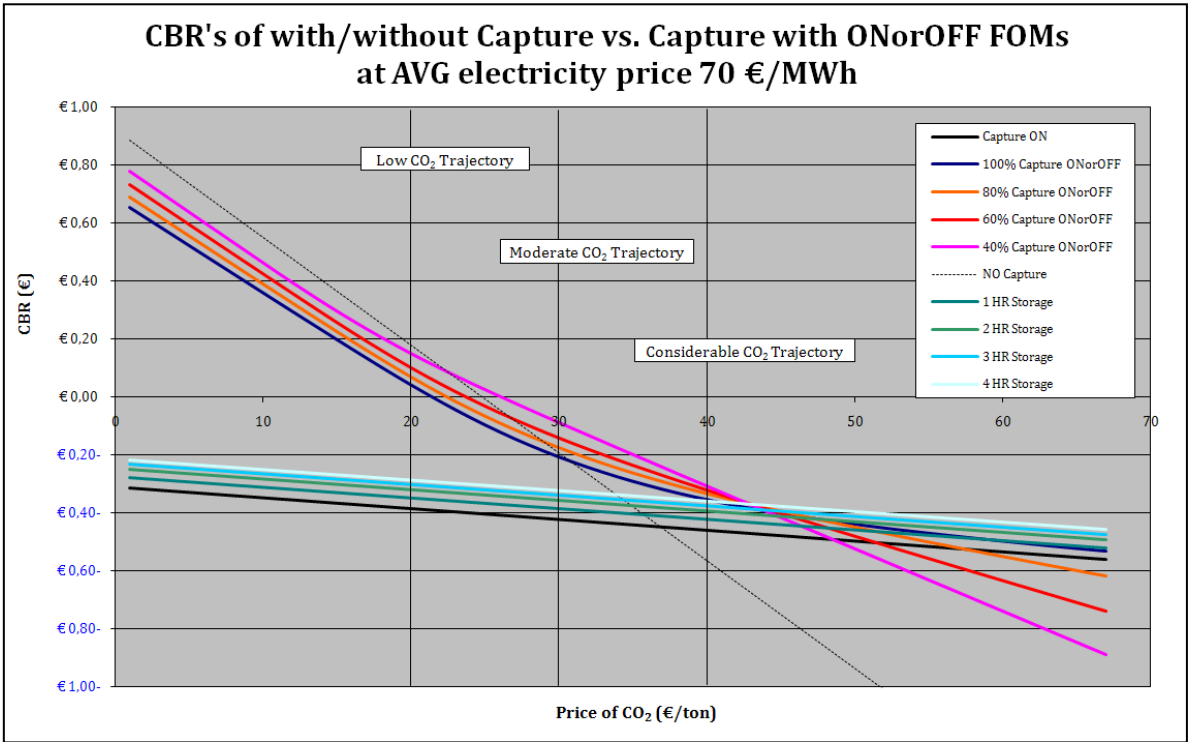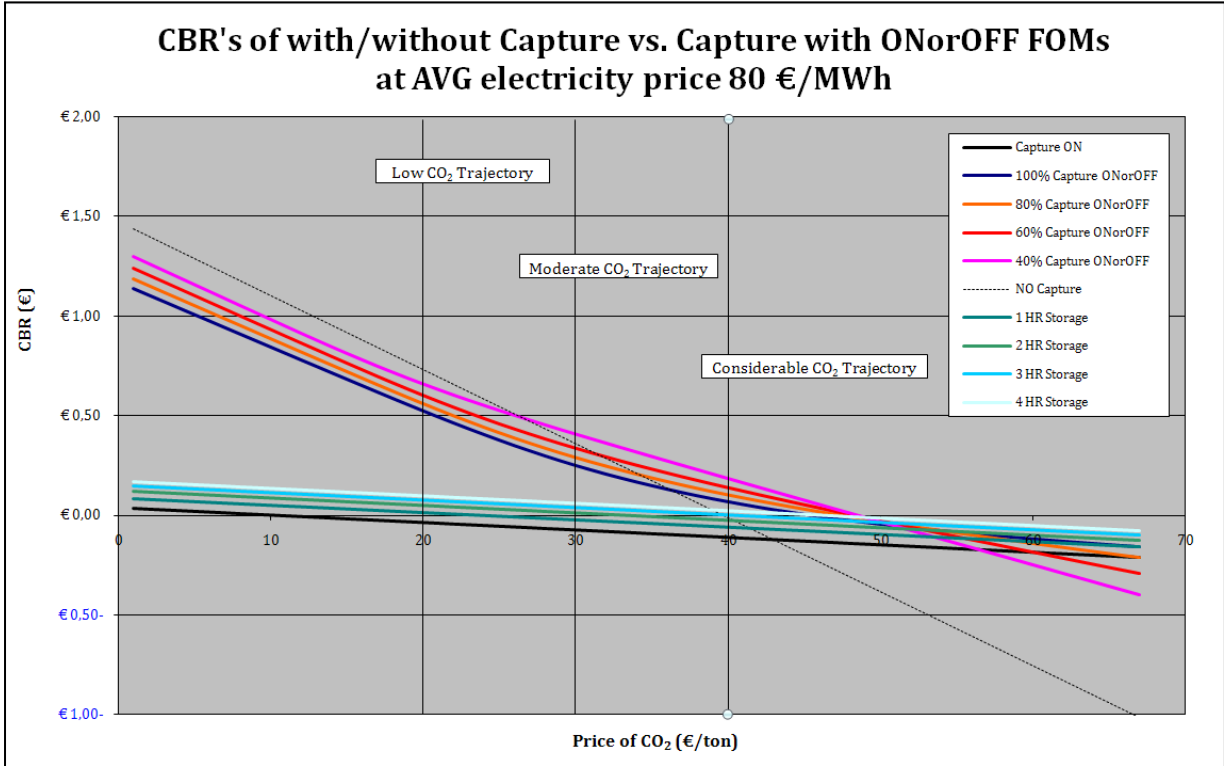

Figure 5-16 CBR's of a coal plant with & without capture and using FOMs at a average electricity price of 80€/MWh

5.4.3 Considerable Electricity Price Trajectory

Almost a doubling of the current average electricity prices by 2025 will increase the business case as shown in figure 5.17. However, knowing that in the last few years the electricity prices for consumers has increased 6-8% annually; the doubling of the average electricity price within ten years seems plausible. Nonetheless, the goal of this scenario analysis is not to define the chance that a certain trajectory will happen, but indicate which FOM could improve the business case using different electricity and CO_2 price trajectories.

Again the 40% capture plant using the ONorOFF FOM performs best at considerable trajectories. Assuming the low / moderate trajectory would occur then a coal plant without capture would only buy credits and continue to emit CO_2; however other decision criteria could impact the decision to invest or not.

So far all trajectories envision a rise in the electricity and CO_2 prices. Should the price of electricity decrease in relation to the 2005-2008 average electricity price then a more negative business case is to be

expected. Furthermore, if electricity prices drop and CO_2 prices increase the option to even run a coal fired plant becomes less feasible. In conclusion, the trajectories present a trend in the performance of the FOMs. Assuming, that the low trajectory is the least optimistic the following observations can be made. At low CO_2 prices (0 to 20-25 €/ ton CO_2) the investment option would be a coal plant without capture, when CO_2 prices are in the region of 25-45 €/ton CO_2 a smaller capture plant is desired (40% capture plant) that employs the ONorOFF FOM. When prices of CO_2 per ton surpass the 45€ mark then a full scale capture plant would seem the logical investment option. In addition an intermediate storage FOM could be added to boosts it performance even more.
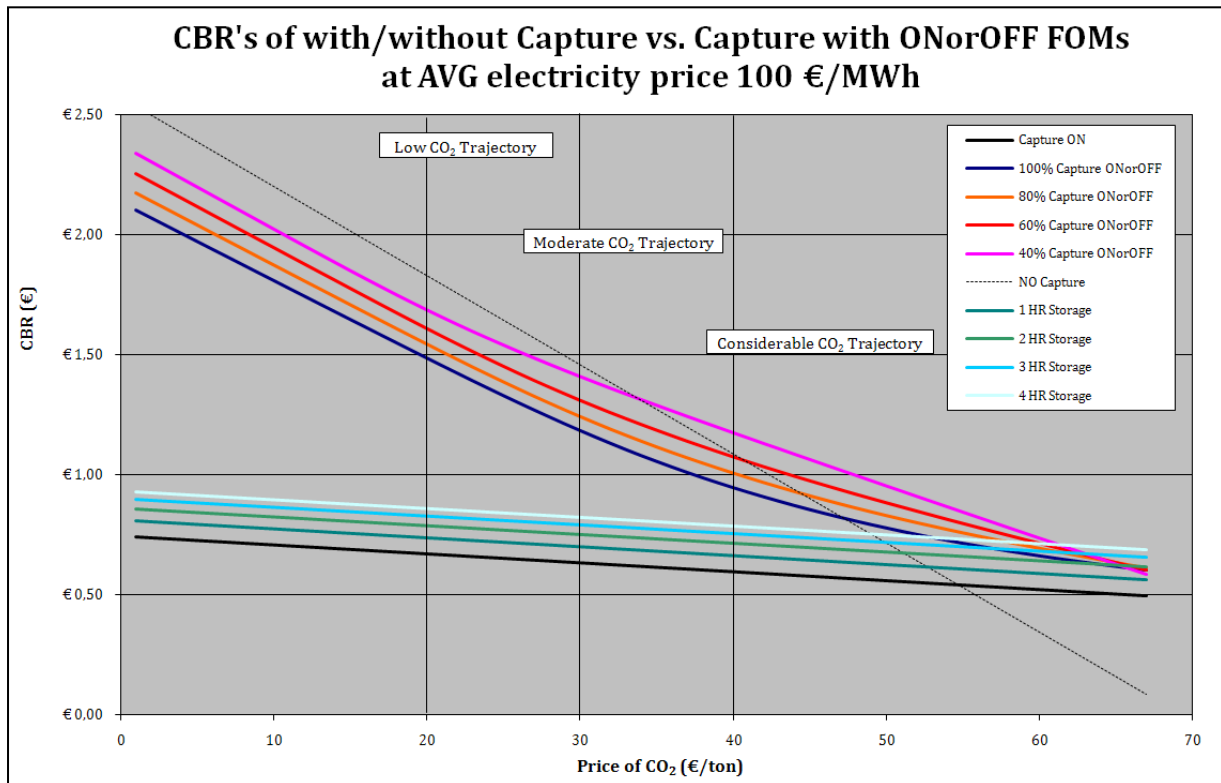
Figure 5-17 NPV's of a coal plant with & without capture and using FOMs at a average electricity price of 100€/MWh

5.5 Synthesis

This chapter had the aim to answer sub-question D: *How do different scenarios impact the results of the model and the business case?* Prior, to answering this question the main results of the FOMs model were presented and discussed. Its conclusions were that implementing FOMs would be operationally beneficial. The two FOMs, ONorOFF and intermediate storage, could provide additional income by exploiting high electricity prices. The ONorOFF FOM made a consideration whether or not to keep the capture plant running based on the cost of electricity and the price of CO_2. Intermediate Storage only uses the price of electricity to base its decision. In general, it was found that ONorOFF provides the plant operationally with best of both worlds; being able to reduce CO_2 costs when needed and exploit high electricity prices should they occur. Furthermore, using smaller capacity capture plants (40% in particular) is beneficial at lower CO_2 prices.

Having established that FOMs, at a plant with capture, provide an operational edge, a cost Benefit Analysis was done. Using a CBR, the investment costs could be valued against the operational income. It was quickly found that any form of capture would yield a negative business case. However, the CBR was still used to compare the FOMs. From this analysis it was found that the capital investment for; a) a smaller capacity capture plant, b) switching the capture plant ONorOFF, and c) any hours of intermediate storage yielded a better (less negative) business case. An argument why these business cases were negative was presented in 5.2; NPV's lack opportunity costs, and therefore doesn't consider that waiting to invest could proof beneficial. In a future environment, were electricity and CO_2 prices are higher, a more positive NPV/CBR is expected.

Three scenario trajectories for both electricity and CO_2 prices were presented. The goal of these scenarios was to examine the influence of both the electricity and CO_2 prices on the business case of a coal plant with capture that implements the developed FOMs. These scenarios are merely plausible future events but they did demonstrate that one type of capture plant configuration performs stronger than the others. The 40% ONorOFF capture plant consistently out performs the other capture configurations at low to moderate CO_2 prices (0 to 40-45 €/ton CO_2). When CO_2 prices are above 40-45 €/ton CO_2 the desired configuration is a 100% capture plant with intermediate storage. To answer the sub-research question - the FOMs are a robust investment options that will improve the overall business case of a coal-fired power plant with capture. Although, the timing of the decision to invest in these FOMs is dependent on the environment in which they will operate.

Chapter 6 *Summary of Conclusions & Recommendations*

In this chapter the conclusions, of the sub-questions discussed in each chapter, are summarized and further high level conclusions are discussed. The structure of the conclusions and recommendations will be based on the sub-questions. In each section of this chapter, 6.1 throughout 6.4, the knowledge gained from studying the individual sub questions is discussed. Additionally, each section (6.1 till 6.4) will incorporate recommendations specific to that sub questions.

In section 6.5, conclusions and overall recommendations pertaining directly to the main research question: "How can Flexible Operating Mechanisms (FOMs) improve the business case of an Advanced Super Critical (ASC) pulverized coal power plant with post combustion capture?" are presented. Section 6.6, will present institutional and governance issues related to the functioning of the FOMs in the 'real' world. Furthermore, suggestions are given how these issues/barriers could be overcome. Additionally, different market mechanisms and the embedding of these FOMs in the larger system (CCS) will be discussed. In section 6.7, personal reflections on the thesis project, including the process, challenges and achievements, will be shared.

6.1 Flexibility through Capture

This section, 6.1.1, will provide the exploration of the research sub-question; *"what is flexibility for pulverized coal power plants and/with post combustion capture?"* and present its main conclusions. In the next subsection, 6.1.2, knowledge gaps that remain are given in the recommendations for further investigation.

6.1.1 Conclusions

Advanced Supercritical (ASC) pulverized coal power plants are, in general, inflexible and slow to quickly respond to market demands or changes. This inflexibility stems from the process it used to generate electricity from steam by burning coal. Although, the state-of-the-art coal plants incorporate more flexibility, they only represent a small fraction of the coal-fired power plants currently in service. The thesis assumes that CCS will be part of the mitigation portfolio to curb emissions to the atmosphere. In this context, coal-fired plants will have to add capture to their normal operating procedure; or face the threat of paying CO_2 emission rights. The addition of a capture approach is discussed and found post combustion capture to be most suitable. It is concluded that post combustion capture can be connected to existing coal plants. Furthermore, post combustion capture is more mature than the other technologies on the market. From this point on, an ASC pulverized coal power plant with post combustion capture using amines (MEA) will be referred to as a coal plant with capture.

Even though, the addition of capture to a coal plant might suggest a lowering in flexibility. Nonetheless, capture plants can add additional operational flexibility to the coal plant. Albeit, the coal plant may be able to sell less electricity, but it will be able to respond much faster to market demands and changes. One additional service it could provide is auxiliary service; turning the capture plant of will 'free' the inherent energy penalty of capture, and this can be send to the grid in the form of 'extra' electricity. The addition of capture also provides the operator with the choice to either capturing the CO_2 emissions

or pay the emission rights. From the literature it is known that capture has high investment costs with low benefits at low CO_2 prices. In order to improve the business case for coal plants with capture Flexible Operating Mechanisms (FOMs) are developed. Each of these FOMs provides the operator with more degrees of freedom and therefore flexibility. Furthermore, these FOMS are expected to reduce operational costs. The three FOMs developed are:

1. **Capture ONorOFF:** Provides the operator with the capability to turn the capture plant ONorOFF dependent on the price of electricity and CO_2,

2. **Partial Capture ONorOFF:** Installing a smaller capacity is technically not a FOM, but is included as these smaller scales will apply the capture ONorOFF FOM as well,

3. **Intermediate Storage (always ON)**: Intermediate storage has the added value that it can improve the operational income without sacrificing CO_2 capture.

The final observation that pertains to the sub-question is that the ability for the operator to react to market changes without changing the operational status of the coal plant is valuable. Changing the output of a coal plant regularly and frequently will reduce its lifetime and therefore, impact the value of the plant.

6.1.2 Recommendations

This thesis has focused on creating additional flexibility for coal plants that will eventually require capture to maintain their core business; producing electricity through the combustion of coal. It has reached the conclusion that FOMs will be able to facilitate additional flexibility and improve the current business case of a coal plant with capture. However, no exploration was done on the regulatory framework in which these FOMs will operate. Moreover, regulatory constraint could severely constrain the ONorOFF FOM; for instance, an average minimum of capture level of 85-90% or a maximum averaged emissions quota per hour. Therefore, future work should focus on the regulatory uncertainties and analyze which institutions can play a role in defining these regulations. In section 6.6, more of these possible regulatory restrictions are discussed and recommendations given on how these barriers could be reduced.

All though outside the scope of this thesis., further study should also include the technical and social feasibility of applying these FOMs in context with a large CCS network (e.g. contractual requirements with transport parties could limit the amount of hours a capture plant could be turned off to maintain sufficient pipeline pressure and driving force).

6.2 Modeling Flexibility

Based on the research sub-question: "*how can the operational performance of the Flexible Operating Mechanisms (FOMS) be evaluated with the use of a model?*" The proposed model is a techno-economical model that can evaluate the flexible operating mechanisms.

6.2.1 Conclusions

The model is developed using the Excel software from Microsoft. The choice for Excel was based on its strengths; presentation of data and graphical functions. The characteristics of the model can be summarized as; bottom-up, retrospective (ex-port facto) and deterministic. In order to evaluate the FOMs, analytical equations are expressed. From these equations it is expected that the FOMs can provide

reductions in the operational costs. Using the TNO developed base case model initial inputs were either directly derived and where needed adapted and extrapolated. Using the initial inputs the Cost of Electricity (COE - €/MWh) and the Cost of CO_2 avoided (COA - €/ton CO_2) were calculated; found in table 6.1. These two already present an indicative parameter on the value of the FOMS. As expected a capture plant without capture has the lowest COE and COA (dependent on the current CO_2 price).

Table 6-1 the Cost of Electricity (COE - €/MWh) and the Cost of CO_2 avoided (COA - €/ton CO_2) of each Flexible Operating Mechanism

Capture Configuration	Cost of Electricity (€/MWh)	Cost of avoided CO_2 (€/ton CO_2)
Without Capture	31.09	Dependent on current CO_2 price
Capture 100%	50.42	29.37
Capture 80%	44.43	25.35
Capture 60 %	39.54	21.41
Capture 40%	35.39	16.35
Intermediate Storage 1Hr	53.28	33.72
Intermediate Storage 2Hr	54.04	34.87
Intermediate Storage 3Hr	54.80	36.02
Intermediate Storage 4Hr	55.55	37.17

From the analytical analysis it was concluded that the model can calculate the operational performance of the FOMs at a given electricity and CO_2 price. The electricity prices used represent a well distributed dataset but do have some limitations. For instance, the year 2005 shows very high price peaks in comparison to other years in the data set. However, the assumption was made that it is representative when the average yearly performance (over 4 years) is used instead of the performance of a given year. The model also has limitations; it is unable to add trends to the price of CO_2 during a simulation run. Nonetheless, the CO_2 price is varied between the runs and then returns a performance at that given CO_2 price.

6.2.2 Recommendations

The limitations of both the simulation software as the models capability to represent a CO_2 trend over a given year can be a point of further study. Using Excel is useful for keeping an overview of the inputs, outputs and descriptions. However, for more complex calculations, differential equations and matrix calculations, MATLAB would offer more opportunities. The drawback of MATLAB is getting presentable & formatted outputs (graphs). It's not a case of which is better but which is better at which task. For future study it is suggested that a MATLAB model is build that can generate CO_2 trends and manipulate the electricity price data set; i.e. increase or decrease the volatility of prices, changes over a longer timeframe (40 years – lifetime coal power plant).

Another recommendation, for future investigation, is getting experimental data that will allow for more accurate modeling of the FOMs. Much of the inputs are adapted from other TNO models and this increases the risk of unwanted discrepancies. Finally, pertaining to the sub-question, different evaluation techniques could be used. For instance, evaluation based on more than just techno-economic factors; feasibility, public acceptance and the ability to interact with other parts of the CCS system.

6.3 Model Sensitivity

The research sub-question *"Does the model satisfy all verification and validation tests?"* may not be the most interesting one, but it is important to any modeling project.

6.3.1 Conclusions

During the sensitivity analysis, it was found that the model is dependent on 4 input values. The sensitivity analysis of the TNO developed base case model has shown that it is dependent on the price of fuel and the discount rate. The FOMs model is sensitive to changes in the electricity prices and CO_2 prices. However, this is expected as these are the time dependent inputs and determining parameters for most of the FOMs. Nonetheless, the sensitivity analysis has shown the extent of this dependency. The extent of dependency is summarized in table 6.2.

Table 6.2 Impact of changing the average electricity price on the operational performance

AVG Electricity Price	*NO Capture*	*100% Capture ON*	*100% Capture ONorOFF*	*Intermediate Storage 1Hr*
Δ AVG E / OP income	18%	24%	19%	23%

In response to the sub-question it can be concluded that the model has passed the V&V tests but the dependencies will have to be remembered in order to provide clear result observations.

6.3.2 Recommendations

During the calculation verification, also been called numerical error estimation, the numerical error estimation can be calculated using; Error = (Numerical result – Exact result); however, when the exact results aren't known, this type of verification become difficult to complete. In future studies the inputs could be represented with their degree of uncertainty. For instance, capital cost for a coal-fired plant isn't M€ 1,456.18 but rather M€ 1,500 ± 50. If this is done for all estimates the final numerical error can be calculated. In respect, to the observations made in chapter 5, the outcome figure would be: operational income = 120 ± 10 M€/yr instead of 122.35 M€/yr. The first value may not be 'exact' but presents additional information about the confidence level of the outcome.

6.4 Robustness Flexible Operating Mechanisms

"*How do different scenarios impact the results of the model and the business case?*" is the last sub-question that is asked in this thesis. This question implies that both the initial outcomes of the model as well as the scenario results be evaluated on the business case.

6.4.1 Conclusions

From the initial model results, using the 2005-2008 electricity prices and keeping CO_2 prices flat during simulation runs, it was found that the FOMs <u>do improve</u> the business case in relation to cost benefit ratio (CBR) of a coal plant with capture. The emphasis on 'improve' is fitting, as the business case under the initial conditions is negative; i.e. all the capture configurations and with FOMs do not warrant investment. However, an improvement is realized by the FOMs by increasing the value of the capture plant. To study at

which electricity and CO_2 prices, the capture configurations could outperform even a coal plant without capture and have a positive NPV and higher CBR`s than 1, scenarios were described.

These scenarios describe possible trajectories that the CO_2 and electricity prices could encounter. Intentionally, the decision was made not to define the chance that a certain trajectory would become a possibility; i.e. the likelihood that a predication becomes reality is neglected. By increasing the average electricity price of the 2005-2008 electricity data set to 70, 80 and 100 €/MWh (average 2005-2008 is 56.6 €/MWh) the performance of the capture configurations with FOMs improved significantly. Especially, the <u>40% capture plant employing the ONorOFF FOM consistently out performs the other capture configurations</u> at low to moderate CO_2 prices (0 to 40-45 €/ton CO_2). When CO_2 prices are above 40-45 €/ton CO_2 the desired configuration is a 100% capture plant with intermediate storage. To answer the sub-research question - the FOMs are a robust investment options that will improve the overall business case of a coal-fired power plant with capture. Although, the timing of the decision to invest in these FOMs is dependent on the environment in which they will operate.

Finally, it can be said that the current electricity prices will need to be higher to get a feasible business case (CBR>1). However, the evolution of electricity prices within a CCS regime with larger renewable energy sources is of yet unknown. Nonetheless, the average price of electricity will need to be at least double of current prices for the best performing FOM (40% ONorOFF) to have a CBR larger than 1.

6.4.2 Recommendations

Whilst testing the model, with scenarios, the limitations of the model were made explicit. As mentioned in 6.2.2, the model lacks the capability to manipulate the electricity price data set. For instance, a scenario could have been the increased amount of intermittent renewable in the energy portfolio mix. This has a possible effect on the behavior of the electricity prices. Although, the average electricity prices remain the same more fluctuations in electricity prices could cause one of the FOMs to perform better than tested under the conditions in the thesis. The recommendation is thus two-fold; elaborate the capabilities of the model and second, analyze how the energy portfolio mix could alter the trend of electricity prices.

Also further work could be applied to reduce the critiques on CBR/NPV analysis. NPV's and CBR`s don't recognize opportunity costs – waiting to invest later could be beneficial. In order to gain better understanding of the value of a FOM a real option analysis could be done. A final recommendation, pertaining to sub-question D, is to improve the quality of scenarios. In the thesis, the scenario were based on electricity and CO_2 price trends and not based on cause and effect; For instance, should the EU ETS fail to achieve set goals, it could artificially increase the price of CO_2 or remove credits from the market. Therefore, scenarios should be developed that describe the cause and effect and adapt the model to simulate these cause/effects.

A final recommendation has to do with the combination of the two FOMs. It has been shown that intermediate can add a significant annual revenue increase ($\approx$2.5% annually for 3 Hrs storage) to a 100% capture plant that is always ON. Furthermore, intermediate storage doesn't release CO_2 emissions to the atmosphere whereas ONorOFF does. However, what happens when a 40% capture plant that employs the ONorOFF FOM is fitted with an intermediate storage option would be interesting to know.

6.5 Decision to Invest

"How can Flexible Operating Mechanisms (FOMs) improve the business case of an Advanced Super Critical (ASC) pulverized coal power plant with post combustion capture?"

The thesis provides evidence, based on the response to the sub-questions, that FOMs **do improve** the business case of an ASC pulverized coal plant with post combustion capture. Furthermore, the author would support the advice that an investor/operator of a coal plant, wanting to install capture should wait till prices of both electricity & CO_2 are more favorable. When the environment is favorable, an initial investment in a smaller capacity of capture (e.g. 40%), whilst employing the ONorOFF flexible operating mechanism is preferable under most conditions. Should prices of CO_2 rise faster than predicted and an additional 40/60% plant could be added. From the analysis of the economies of scale, the costs of adding a second plant does not decrease the value as a whole.

Another main conclusion that can be drawn, in response to the main research question, is the fact that intermediate storage provides an additional revenue stream should other factors, such as regulation and integration with the CCS value chain, limit the use of switching between full and zero load (ONorOFF). Furthermore, intermediate storage FOM is a dependable and robust option to add to any post combustion capture plant. It is not dependent on the price of CO_2 and doesn't emit any additional CO_2 by operating.

For future work several recommendations have been presented in the response to the sub-questions. Nonetheless, some of these merit more attention than others. The two recommendations that warrant quick attention are; i) the combination of partial scale capture (ONorOFF) and intermediate storage. Do these two FOMs conflict or can they function / operate at the same plant and ii) development of a model that can implement electricity and CO_2 trends.

6.6 High level Recommendations

In the next sections the higher level recommendations are presented. These pertain to the main research question but are focused on institutional and governance issues. The section is subdivided into 3 sections; regulation & governance (6.6.1), institutional & markets (6.6.2) and contracts & public acceptance (6.6.3). For clarification, CCS encounters many barriers and especially for the storage segment; these include monitoring, public acceptance and ownership issues (both of the storage site as the gas). However, these higher level recommendations are focused on issues that have a direct effect on the embedding of the application of the FOMs. Note, these are recommendations and not deeply researched topics; i.e. they are an advice for possible future work and/or study.

6.6.1 Regulation & Governance

Currently CCS, on an EU level, is guided by a number of different pieces of legislation; the CCS Directive; the Environmental Liabilities Directive (ELD); the European Trading Scheme Directive (ETS) and the Integrated Pollution Prevention and Control Directive (IPPC) (EU commission, 2009). The EU has shown itself to be dedicated to the endeavor called CCS. Furthermore, the EU has agreed upon a directive. The CCS Directive entered into force in June 2009 and member states have until June 2011 to transpose it into their national laws. The plans also include 12 demonstration plants operating by 2015. The Directive

is structured as enabling legislation and does not mandate that capture technology is fitted to coal- and gas-fired power plants. Instead, it provides the necessary regulatory framework upon which deployment could move forward should member states choose to pursue it. In other words, gas and coal plants will have to be capture-ready (have enough space near production to facilitate capture).

This progression in decisions by the EU provides a possible direction of likely future operating environments for coal power plants. CCS will come to pass and coal power plants will have to comply and build capture plants. However, the decision to invest in a capture plant can still be postponed. As long as CO_2 prices remain at current levels the driving force to build is negligible; i.e. fossil fuel plants will pay the tax. The regulations and directives described above are to promote or instigate investment in capture technologies and are therefore beneficial for the successful application of the FOMs. However, some regulations that are proposed could limit the functionality of the FOMs. One of these regulations is the European experience with SO_x and NO_x emissions under the large combustion plant directive (LCPD). These employ an Emissions Performance Standard (EPS); limit emissions to the atmosphere to a certain degree (Wartmann et al, 2009). Should these restrictions be applied to CO_2 then all FOMs except intermediate storage would function. Even if the limitation of emissions is 50% of annual emissions, the effectively of the application of the FOMs (except intermediate storage) is reduced. Operators will have to estimate when turning the capture OFF is valuable and remember the annual quota.

The governance of a CCS system is as yet undefined and only discussed in literature with diverging views; public vs. private operation, central- or decentralized capturing and ownership. Furthermore, the governance of the whole CCS system versus the governance of the parts (capture, transport, storage, post-usage monitoring) is a hot topic of debate. However, of main interest to the main research question is how governance of the CCS system could impact the capture operation. The type governance that will be used is dependent on the structure of the system and the market. In section 6.6.2, the markets in which a coal plant with capture will have to operate are discussed in more detail. For now, the structure of CCS is non-existent and future structures can take different shapes. Initially, the CCS system will most likely consist of small localized, central and linear systems. For instance, a capture plant connected to a single transport pipeline to an offshore field. Several of these systems could be located across a nation but will not yet be integrated. These 'simple' CCS systems have other limits, restrictions and barriers than larger systems structures with higher levels of integration. A larger system could accommodate several power plants turning their capture OFF since other sources of CO_2 are still being captured and transported. This means that the transport actor will keep a level of driving force (the CO2 needs to be at a certain pressure and volume to enable transport). For smaller (initial) CCS systems this will be harder to facilitate and justify turning the capture OFF or storing solvent without stripping the CO_2. On danger of this will be herd behavior; i.e. that all could turn off their capture to benefit from favorable situations.

The uncertainty which governance structure and regulatory framework will be used is the greatest obstacle. Without clear 'rules of the game' it will hard to state exactly which structure or framework will impact the future performance of the FOMs. However, hedging against these risks is always a smart move. In this respect the intermediate storage FOM has an advantage in respect to switching ONorOFF. From a perspective of an investor interested in adding capture to a coal plant, a clear

and upfront understanding of the possible future governance and regulatory framework is essential. Furthermore, a less strict policy towards capture rates and quotas (i.e. allowing FOMs) could expedite investor decision making.

6.6.2 Institutions & Markets

In a future CCS system, many changes will occur within the markets and the involvement of institutions. This section will present how the changes in the APX (consumer behavior, competition with other fuels such as gas fired plants / renewable) and EU ETS could influence the decision to invest in capture plants utilizing FOMs. Furthermore, the role of the Transmission System Operator (TSO) will impact the usage of the FOMs.

The period in which large scale CCS will most likely come to fruition (authors assumption) will be around 2020-2030. Assuming that the APX is still in use and all electricity will be sold through this market the following changes can be expected; through increase renewable the prices will be generally lower but higher fluctuations will ensue. The intermittency of renewable causes these fluctuations; it's in these periods that electricity will need to be generated through other means. Initially, prior to the nuclear disasters in Japan 2011, nuclear power was opted to provide additional electricity. However, favorable attitude towards nuclear has decreased and therefore fossil fuels will need to cover the gap in supply. This means that coal power plants will have to compete with natural gas-fired power plants. Both gas and coal will have to pay the taxes for their emissions or capture them. The difference in costs favor coal to be the main base load supplier; nonetheless, natural gas is becoming more competitive and its capability to quickly ramp up and down to give it an edge in the auxiliary markets (will be larger with the introduction of more renewable sources). The FOMs will provide coal power plants with increased flexibility by switching between ONorOFF. Nevertheless, the action to switch off or on will dependent also on the prices of CO_2.

The price of CO_2 is set by the EU ETS. This market has been setup with the goal to curb emissions and work on the principle 'polluter pays'. Currently, the price for CO_2 is 15-16 €/ton and this is too low to warrant any capture investment; i.e. paying the tax is less costly. In phase III the EU ETS will decrease its credits on the market by 1.74% and therefore create shortages in supply with an expected rise in demand should increase the price for CO_2. Consequently, investment in capture technologies and a whole CCS becomes more feasible. By applying FOMs the investment in capture technologies at power plants could be expedited; however, this will only hold true if CO_2 prices will continue to rise / stay stable at higher prices. Through market imperfections and failure this market could collapse; as happened at the end of phase I, when it was discovered that too many credits had been issued through the National Allocation plans (NAP). Therefore, monitoring of emissions will need to continue to ensure a functioning market; should this not happen and the market fail yet again strong changes could be expected; for instance, stronger regulation and closer institutional oversight to maintain a working CO_2 market. The actor most likely to maintain the system oversight is a TSO. Similar to the electricity grid TSO a CCS TSO will need to monitor flows within the system and the emissions by other sources.

Both the electricity and CO_2 markets will undergo several changes that will influence its current character. This uncertainty, how prices will change, causes great anxiety amongst investors and operators

alike. Also the consumer behavior will change over the coming years; more and more consumers are opting for 'green' electricity and actively trying to reduce their carbon footprint. This would suggest more renewable to be built and this seems to be the case; however, this provides challenges for the TSO. The introduction of more intermittent sources, such as wind and solar, reduces the overall stability of the grid. Therefore, it is expected that fossil fuels, in absence of nuclear, will have to provide these services to balance demand and supply. Furthermore, the introduction of electric transportation will increase the demand for centralized produced electricity; i.e. unless renewable could cover these increases in demand coal and gas-fired power plants will have to provide the deficit.

How do these changes in the market and institutions impact the FOMs? The answer to this question is not straightforward; there are market changes that would benefit the FOMs capability to perform and there are those that reduce the functionality of them. These changes in the markets impact the FOMs on an economic level; the price of electricity and CO_2 influence the value of the FOMs. Furthermore, institutional changes impact FOMs on their capability to function; i.e. will turning OFF the capture be allowed by the CCS TSO? Moreover, does turning OFF the capture plant bring the whole value chain of CCS in jeopardy? One could imagine that transport parties will not be in favor of the ONorOFF FOM as it reduces its transport capability and income; should capture plants share the profits from turning OFF or temporary storage with other parts of the CCS value chain? These questions lead to the next section where more of these issues are discussed. In conclusion, the recommendation will be to analyze how electricity and CO_2 markets will change, both in value and behavior, and examine how the FOMs would function then. Moreover, analyze the institutional organization in which the coal plant with capture applying FOMS will have to operate in and how these parties view these practices.

6.6.3 Contracts & Public Acceptance

In this section contracting between parties in CCS are discussed as well as public acceptance on the application of FOMs. The contracts between parties; i.e. the coal power plant and its consumers / partners in a CCS network will define the total benefit of the FOMs. Furthermore public acceptance on the use of FOMs could influence regulation and/or market behavior.

Currently, coal power plants sell their electricity either through bilateral contract and/or on the APX. In section 6.6.2 the selling on the APX has been discussed. The other type of selling the coal power plants do is through the use of bilateral contracts with large private users; i.e. aluminum production, production industry and other large users. These users need reliable energy sources that can supply without fail; for this reason the switch to intermittent sources is less likely in the short to medium timeframe. These contracts consist mainly of fixed tariff for a certain amount of electricity at a certain time schedule. Although, newer bilateral contracts include the possibility to switch between spot market prices and those used by the power plant supplier, the impact of the FOMs is similar. By the application of the FOM a coal plant can compete with the spot market. For instance, if the spot market prices are high, the coal plant will turn off its capture plant and thus produce more electricity that it can sell at those prices. However, the coal plant operator could also use this gain in profit to compete with other suppliers; i.e. lower prices to be a more attractive trading partner. Again, these are not researched statements but

recommendations for future work. It still will have to be analyzed if the FOMs could provide this competitive edge.

Due to uncertainty of the future development of the electricity and CO_2 prices hard statements about the FOMs impact of contracting is uncertain too. Nonetheless, one could imagine that contracts with other members in the CCS network will have an impact on the value and functionality of the FOMs. One example, that has been described previously, is the contracting with transport parties; can the capture plant be turned off at will or will this impact the downstream function of CCS? These issues will have to be negotiated prior to design and construction. These contracts between parties within a CCS network will have to be clear and well understood; leaving no room for misinterpretation that could lead to the whole system failing. Initially, turning the capture plant ONorOFF could not happen as the system is not robust enough; however, should the system integrate more suppliers of CO_2 then FOMs could be used by a limited number of parties, including coal power plants, more freely. Albeit, these are speculations and will have to be examined in more detail in future research.

Public acceptance has shown to have a strong impact in the early stages of CCS demonstration projects; Barendrecht in 2010 provides a clear case that public opinion can halt projects even before they begin. The NUMBY (Not Under My Back Yard) principle applies here. Can public acceptance reduce the effectiveness of FOMs is an interesting question. One could imagine that public opinion on the emission of CO2 is hardened and subsequently influence policy. This could directly affect the regulators to develop stricter emissions laws; therefore, the option to turn capture ONorOFF is reduced or even lost. Intermediate Storage will be less impacted by public opinion as it doesn`t create higher emission through its use.

The recommendations presented in 6.6 are, in part, based on arguments provided by literature sources but most are speculative of nature. However, the recommendations aim to present the remaining issues that weren`t within the scope of the initial research question. Nonetheless, these issues will have an impact on the usability and value of the FOMs in the 'real' world. These posed challenges for the FOMs will require additional research to examine the true value of each application. In combinations with the earlier stated recommendations and these recommendations can be used by TNO and TUDelft to develop more research projects that either analyzes the FOMs on a higher or more detailed level.

6.7 Reflections on Thesis

The reflections on the thesis are the authors' impressions on the thesis process, methodology and overall achievement. These are personal in nature and should be read as such. First, the thesis process will be discussed; this includes how the project evolved and reached its final product. Secondly, the methodology used by the author is discussed and which weaknesses and strengths of this method came to light. Followed, by the reflection on the green light meeting and the issues that came to light; integration of institutional issues. Last, the overall achievement of this report is reflected upon.

Process

The process, by which this thesis came into being, can be likened to a twisted mountain pass; swerving from one side to the other but nonetheless the summit gets nearer. During the initial stages of this thesis all seemed well and smooth. TNO had an open question that could be interpreted freely by the author. The main focus for TNO was improving (increasing realism) in the business case of post combustion capture. This was both a blessing and a curse. It took a long time to formulate a thesis proposal that was focused enough and feasible. After further discussions with my supervisors a decision was made to develop a model that could evaluate the techno-economic performance of flexible operations at a coal power plant with post combustion capture. Unfortunately, one of my daily supervisors at TNO left to pursue a career in teaching at Rotterdam University and this presented the author with some additional challenges. At this time I only had one supervisor at TNO; Earl Goetheer was initially intended to be a (bi) weekly supervisor and would now function as my main supervisor at TNO. Again, this was both a blessing and a challenge; Earl Goetheer is, in my opinion, one of the most knowledgeable researchers within the field of CO_2 capture and separation technologies. Unfortunately, many others agree and therefore Earl Goetheer had many responsibilities other than supervising me solely. His inputs steered me in the right direction and aided in defining my thesis proposal. The decision was made to develop a model that could evaluate the techno-economic performance of flexible operations – later named Flexible Operating Mechanisms (FOMs).

Once the decision was made to develop a model the road straightened and became clearer. The modeling phase was interesting and rewarding. Many hours have been spent in making the model and analyzing the outputs. I was told in advance that making a model will take a lot of time and that my planning might have been too tight. My supervisors were proven right, modeling did take longer than I expected. Looking back at the whole process from start to a final product, I believe that I would have changed my starting attitude; be more focused on the deliverables rather than endless exploration of the model. I also found that I relied too much on my own faculties during the beginning and middle part of this project to complete this research alone; only in later stages I used the aid off others. In retrospect I would have involved others sooner and made my uncertainties known. This is not only a personal lesson I learned but would recommend all others writing a thesis to utilize the offered support to the full.

Methodology

The methodology chosen to model the FOMs was quickly done on the basis of the authors competencies; i.e. developing models in Excel. Furthermore, the base case models developed by TNO were also developed in Excel and made sense doing the same. Excel is a great tool to keep track of inputs,

calculations and outputs but has limitations when it comes to complex equations such as matrix calculations and differential equations with feedback loops. The modeling of the FOMs initially didn`t foresee any feedback loops but future work as presented in the recommendations do; therefore, for future modeling of the FOMs it is suggested that MATLAB or a similar software package is used. The Excel FOMs model does provide initial exploration and evaluation of the FOMs and can consequently provide which application has merit for future work.

The overall thesis methodology was, as mentioned in the process reflection, not as smooth as could have been. The literature research took longer than expected and even then changes, with the aid of my supervisors, were made after the initial proposal was presented. The modeling of the model took longer than it needed too and cut into the planned writing of the deliverables (the report and the scientific article). My advice for other graduate researcher that plan to model should allocate enough time and then some for the modeling process. Furthermore, in parallel start to write the deliverables; personally I could have written the first 3 chapters at the same time I was modeling the FOMs.

Green light Reflection

The green light evaluation can be found I appendix D. The main advice was to integrate more institutional issues in the final chapter of the report to offset the strong techno-economic nature of the research. Being a student at technology, policy and management it is expected that both technical solutions as institutional / governance issues are present that culminate in a more comprehensive advice to the client; even if the client only asks for a techno-economic business case. To integrate the feedback from the green light meeting several changes have been made to the report. One of the major changes was the inclusion of higher level recommendations. Recommendations that surpass the client expected techno-economic evaluation of the FOMs and provide how institutional/governance issues could reduce the effect of the FOMs overall.

Overall Achievement

After integrating the feedback from the green light meeting the report has become more balanced; including both the techno-economic evaluation of the FOMs and recommendations on institutional and governance issues. The institutional and governance issues that could impair the functioning of the FOMs in the 'real' world have been further deepened in a scientific article (appendix C). My personal attitude on the final product is one of pride and the lessons learned (some harder than others) during this process will prepare me for future research challenges.

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Appendix A Electricity Price Analysis

This appendix will present the electricity price data set more detailed than the graph in chapter 3. The graphs for all the 4 years are illustrated together with the daily average prices. Furthermore, the distribution of the electricity prices over the 2005-2008 periods is presented.

A.1 APX provided Electricity Prices

The APX-group provided hourly electricity price data through the Copernicus Institute Utrecht for the period 2005-2008. This large data set of prices makes it possible to asses' hourly performance of the FOMs. In figure 3.1 (chapter 3), a segment of the data set is illustrated; the graph shows the electricity prices for the period January 2005 - December 2005. In this section the whole graph is presented from 2005 till 2008.
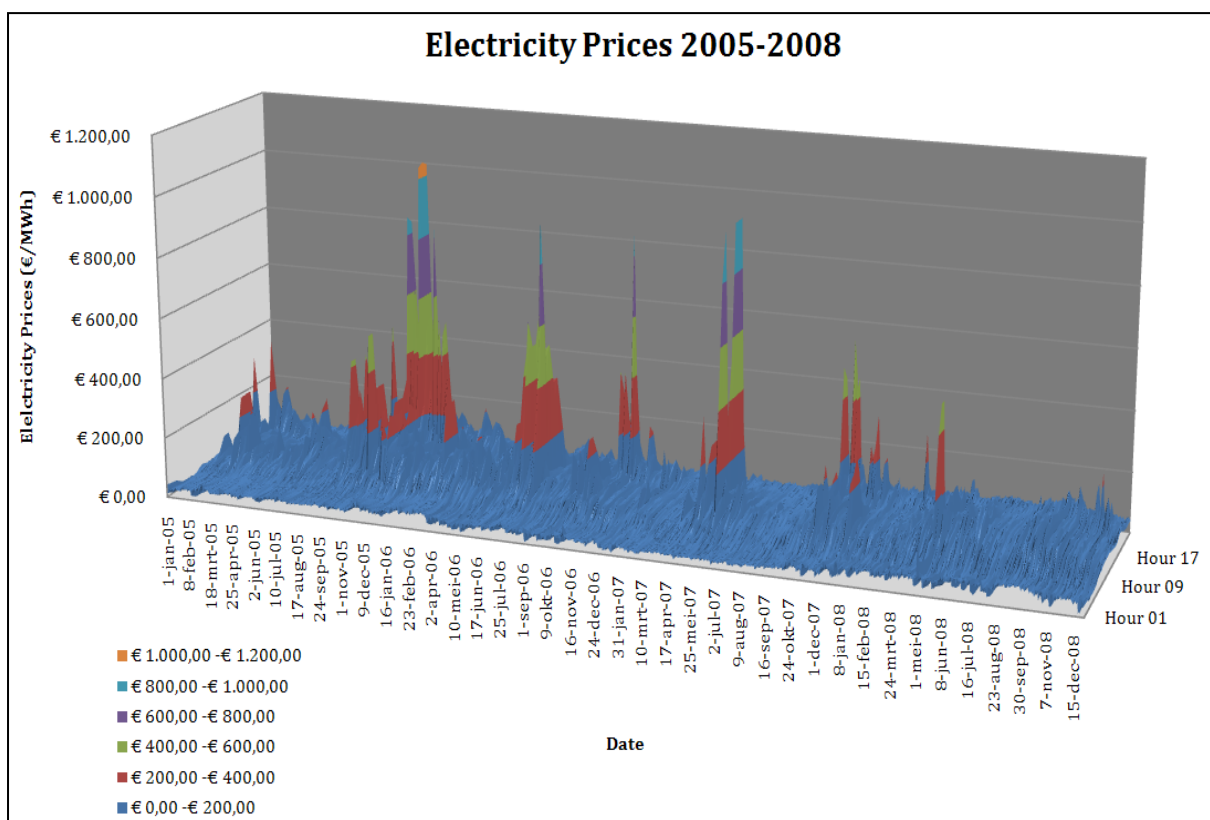

Figure A-1 Electricity prices 2005-2008

A difference between the years can be seen; 2005 has more frequent peaks than 2008. However, the average price is higher in 2008. For further analysis the distribution of the electricity prices is illustrated in figure A.2. The distribution of the electricity prices is created using the @RISK software package by Palisade for Excel. From the distribution it can be seen that most values hover around the average electricity price (similarly to the cost of electricity - €50 /MWh). This is understandable as this is the marginal costs of the electricity producers.
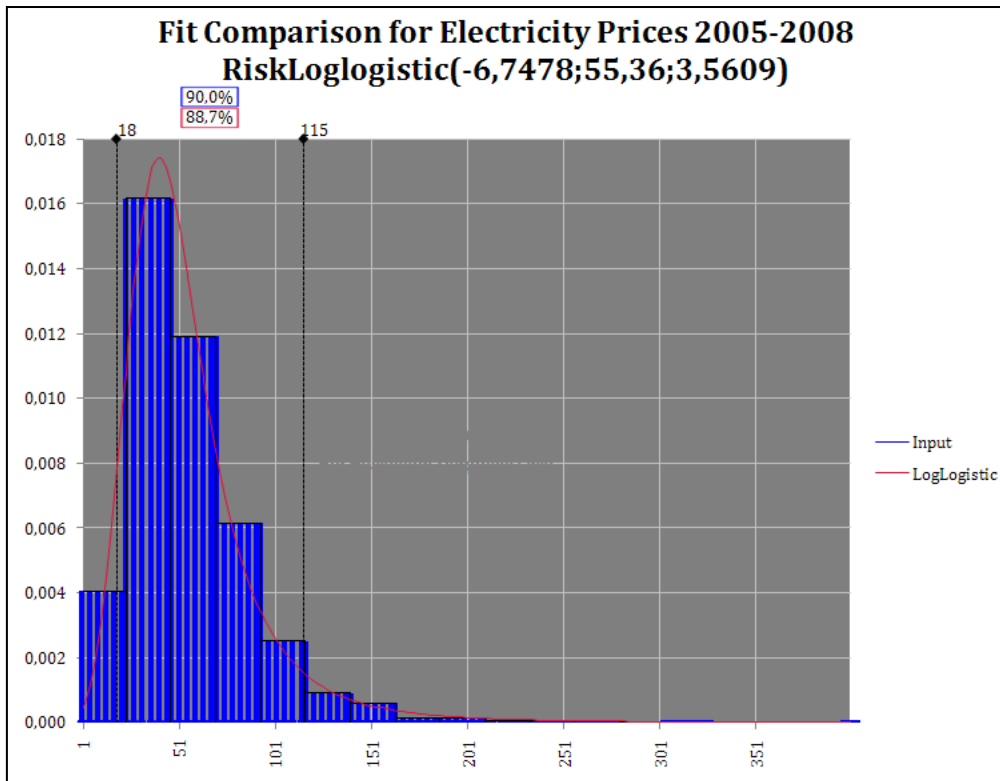
Figure A-2 Distribution electricity over period 2005-2008 (create with @RISK)
x-axis = €/MWh, y-axis = Frequency

From the whole data set graph (A.1) and the distribution (A.2) it can be seen that only a few moments per year the electricity prices are extremely high. In general they are with the range €18-115 (90%). Looking at the annual average electricity prices per day presents more moderate values for electricity. Nonetheless, peaks still persist around noon and 19-20pm. The differences per year are clearly shown. With 2006 having the highest peaks at noon and 2007 being a very low price year; furthermore, 2008 is in general a higher price year than all other years. This is illustrated in figure A.3
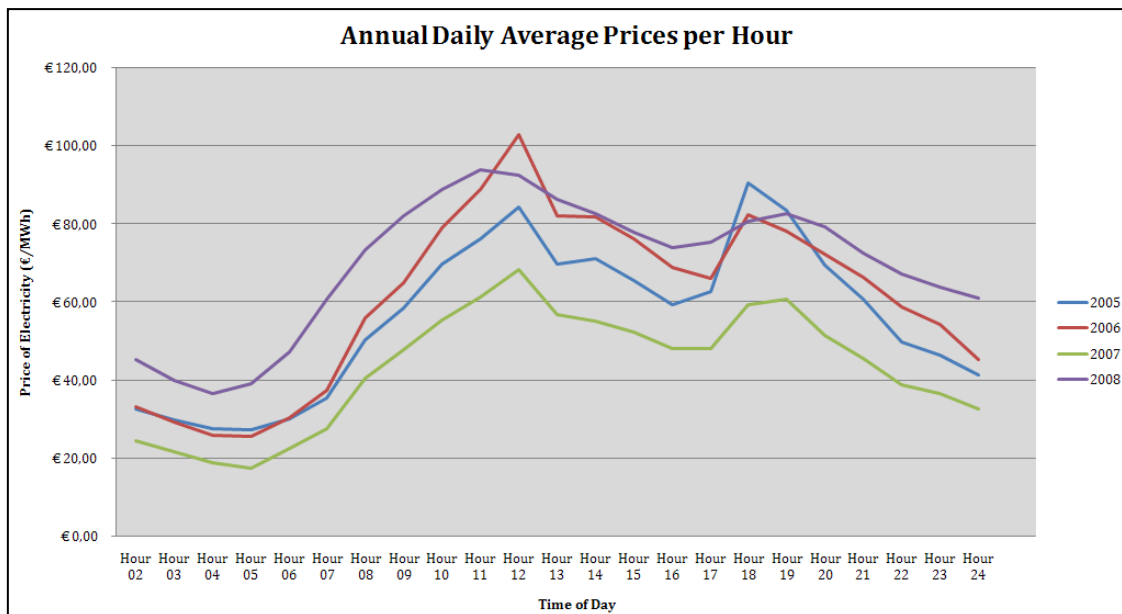

Figure A-3 Average daily electricity prices per hour over a given year

Appendix B FOMs Model Manual

This appendix will present the guidelines and functioning of the model. Each thesis hardcopy will be provided with an USB memory stick that will include the excel model. The digital submitted version of this thesis doesn`t include the attached model. If interested, contact TNO Separation Technology, Delft and request a version of the model. This manuals aim is twofold; i) demonstrate how the model can be operated and ii) present the coding of the different FOMs. The structure of the appendix is the following. First an overview of the model is shown, followed by an explanation of the inputs, calculations and outputs. Finally the graphing of the results is explained.

B.1 Model Overview

The model has three distinct parts; inputs, calculations and outputs; each of these three parts will be a sub-section of this appendix. In figure B.1 the model overview is depicted and illustrates how the model is built up. In the subsequent sections the various segments of the model are explained. The model file is called: FOMs Model MSC Thesis project Marinus Verbaan.xlsm. When the file is opened the Marco content will have to be enabled. The function of the Macro will be discussed in the section on model outputs.
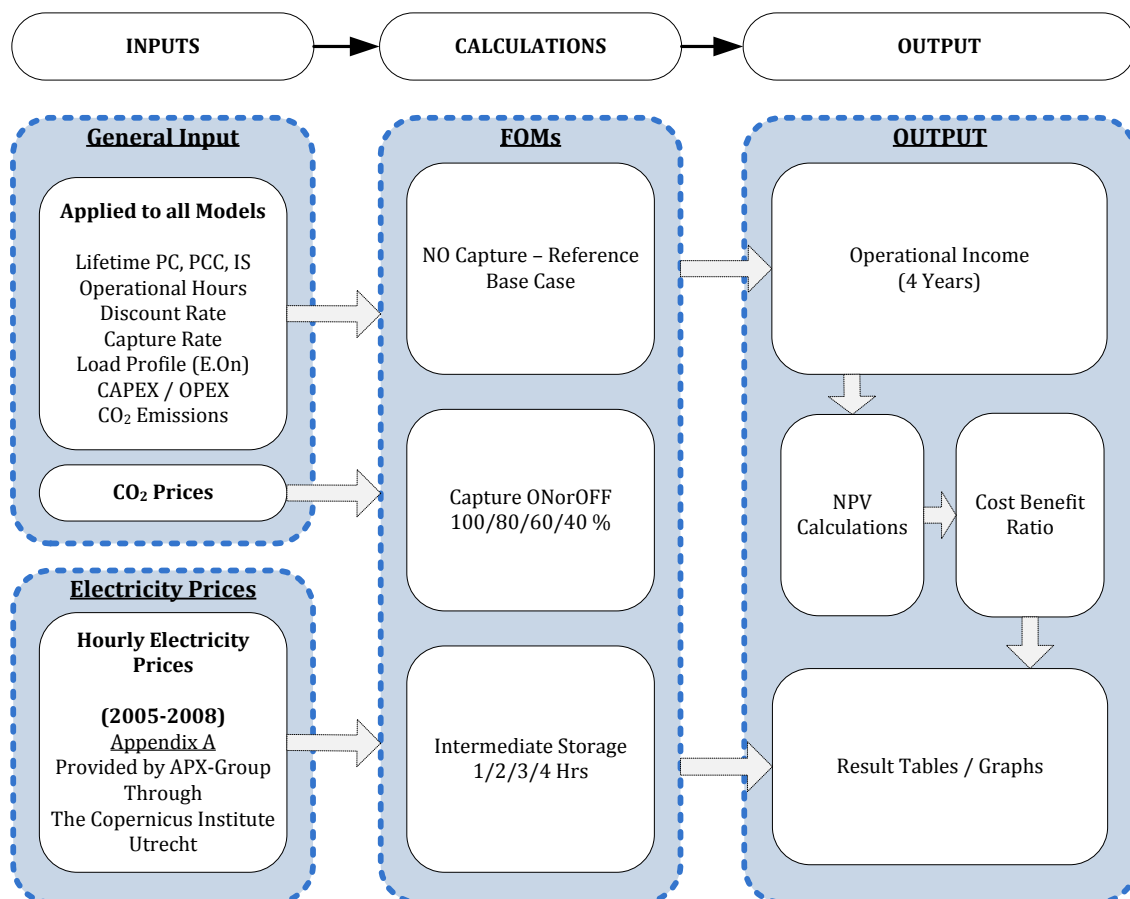

Figure B-1 Model overview

B.2 Inputs

The model makes use of multiple inputs that are specific to each FOM and are used in different equations. These equations are analytically described in chapter 3. In figure B.2 the print screen depicts the input screen of the model. In this picture several parts have been numbered and are consequently clarified.

Figure B-2 Excel Model Input Screen

1   The general inputs consist of the lifetime of a coal power plant and the lifetime of a PCC plant. Most of the inputs are straightforward. Attention must be paid to the units. Other inputs in the first table are the amount of operational hours, the capture rate of the capture plant and the discount rate. The CO_2 price is an input that is changed by a macro when running multiple simulation runs. This will be discussed later on. Finally the e-price factor is the percentage by which the average price of electricity can be changed.

2   The inputs in this table are the economic, production and environmental inputs for the capture plant as well as the partial capture scaled plants. The economic inputs consist of the CAPEX and OPEX costs. Attention must be paid to the inputs for the capture plants; these are additional costs above the investment of a coal power plant. The production inputs described how much net and gross electricity is

produced in a specific configuration. Finally the environmental inputs give a numerical value for the amount of emitted CO_2.

3 The inputs are automatically generated after table 2 is filled in. It translates the values in table 2 (M€) to hourly costs. This is done also for the CO_2 costs at the low and high profile loads. The load profile has a table in the input screen but is underneath those shown in figure B.2. The current used values for the load profile are; low=0.41 and high=1. Note, that all the tables have an ID. This ID describes the format how a specific cell is named. The naming of the ranges aids in understanding the calculations (coding) done later on.

4 The last inputs are focused on intermediate storage. The inputs are the first two rows of CAPEX and OPEX. Note that the OPEX costs are calculated from the COE and not dependent on the actual electricity price.

Finally the input screen has a table that calculates the cost of electricity and cost of CO_2 avoided. These aren't input but aid the user in seeing direct result of the changes in the input on these values. These two indictors are used frequently in the literature and therefore act as a verification that the inputs are within reasonable limits.

The last input values are the electricity prices. These will form the basis of the model and are found on the third tab of the model. The actual values of the electricity prices have been described in appendix A. The fourth tab adjusts the electricity prices with the electricity price factor described in table 1.

B.3 Calculations

This model has many spreadsheets that calculate various capture configurations and FOMs. Below the calculation tabs are shown that calculate the hourly performance of each FOM. The first calculation tab is NO CAP and the last one is IS 4HR.

INPUT ALL | 2005 Ep | EP | Adj EP | NO CAP | CAP 100% | CAP 80% | CAP 60% | CAP 40% | IS 1HR | IS 2HR | IS 3HR | IS 4HR

In this section the calculations are described per tab. The description will present the coding used and the decision criteria to operate the capture plant or not.

Every spread sheet calculates the hourly performance; each day has 24 hours and there are 4 years (1460 days). In the illustration below a segment of the table is presented. When the values are blue the hourly operational performance is negative; i.e. a loss is made (black is positive). These values below are very negative as this is after the calculations at a high CO_2 price (€67 per ton CO_2).

PRICES	Hour 01	Hour 02	Hour 03	Hour 04	Hour 05	Hour 06	Hour 07	Hour
1-jan-05	€ 23.383,36-	€ 24.576,82-	€ 25.431,18-	€ 29.789,45-	€ 30.603,93-	€ 30.284,79-	€ 51.021,35-	€ 50.80
2-jan-05	€ 30.786,77-	€ 34.869,11-	€ 35.490,77-	€ 36.434,90-	€ 36.434,90-	€ 36.434,90-	€ 61.152,22-	€ 60.24
3-jan-05	€ 32.548,69-	€ 33.113,84-	€ 35.826,53-	€ 36.272,00-	€ 36.052,59-	€ 36.029,32-	€ 41.255,78-	€ 30.44
4-jan-05	€ 30.121,89-	€ 30.633,85-	€ 31.285,43-	€ 31.950,30-	€ 32.013,47-	€ 31.720,92-	€ 44.924,97-	€ 37.01
5-jan-05	€ 28.246,94-	€ 28.855,30-	€ 29.832,67-	€ 30.706,98-	€ 30.806,71-	€ 29.437,07-	€ 40.297,89-	€ 33.56
6-jan-05	€ 28.393,21-	€ 28.958,36-	€ 29.982,27-	€ 30.853,26-	€ 31.119,21-	€ 30.022,16-	€ 42.002,60-	€ 36.40
7-jan-05	€ 29.669,77-	€ 30.670,41-	€ 31.391,81-	€ 32.216,25-	€ 32.448,96-	€ 31.687,68-	€ 46.142,62-	€ 38.18
8-jan-05	€ 29.250,90-	€ 31.059,37-	€ 31.850,57-	€ 32.781,40-	€ 33.130,46-	€ 32.116,52-	€ 49.576,40-	€ 46.78
9-jan-05	€ 26.465,07-	€ 29.347,31-	€ 31.784,08-	€ 33.599,20-	€ 33.782,04-	€ 33.775,39-	€ 55.762,08-	€ 53.90

NO CAP: this spreadsheet calculates the hourly performance of a coal power plant without capture. The calculation is an operational one; therefore the capital costs aren't used. The capital costs will be used to evaluate the investor decision to invest or not in hindsight. The code used to calculate the hourly performance is: (note-the NO denotes that no capture is installed). The exact values of the calculations are dependent on the input values as described in figure B.2. The coding is for the first hour of the data set.

(('Adj EP'!B4*NET_PCC_NO*LOAD_LOW)-(OPEX_PCC_NO+CO2_LOW_NO))

Where,	NET_PCC_NO	= Electricity produced to be sold
	LOAD_LOW	= Low load profile (23 → 7 am); high would be between the other hours
	OPEX_PCC_NO	= Operational costs per hour without capture
	CO2_LOW_NO	= Amount of CO_2 emitted during the low load profile
	PRICE_CO2	= Price of CO_2
	Adj EP	= Adjusted electricity price

The coding shown above is for a low load profile hour. For high load hours the value for LOAD_LOW changes into LOAD_HIGH.

CAP 100%: This spreadsheet consists of 4 large tables. The first table calculates the performance with capture ON, the second table is capture OFF and the third chooses which individual hour has a higher revenue or lower cost. The last table counts when the capture plant is turned on to calculate the utility of the capture plant.

Capture 100% ON	B4=('Adj EP'!B4*NET_PCC_100*LOAD_LOW)-(OPEX_PCC_100+CO2_LOW_100)
Capture 100% OFF	AB4=('Adj EP'!B4*NET_PCC_NO*LOAD_LOW)-(OPEX_PCC_NO+CO2_LOW_NO)
Decision ONorOFF	BB4=IF(B4>AB4;B4;AB4)
Utility at a given hour	CB4=IF(BB4=B4;1;0)

Note that capture OFF is the same operationally as NO capture. The model assumes that the maintenance costs for the capture plant are negligible in relation to the operational costs when the capture plant is turned ON. The modeled decision methods to have capture ONorOFF is based on a simple principle; if OP $_{off}$ > OP $_{on}$ then Capture OFF else Capture ON.

CAP 80/60/40%: These spreadsheets calculate the same as the 100% capture but use different inputs. The coding for 80% is presented below to illustrate the difference between 100% and a partial capture plant (scaled down).

Capture 80% ON	B4=('Adj EP'!B4*NET_PCC_80*LOAD_LOW)-(OPEX_PCC_80+CO2_LOW_80)
Capture 80% OFF	AB4 =('Adj EP'!B4*NET_PCC_NO*LOAD_LOW)-(OPEX_PCC_NO+CO2_LOW_NO)
Decision 80& ONorOFF	BB4=IF(B4>AB4;B4;AB4)
Utility at a given hour	CB4=IF(BB4=B4;1;0)

The main difference can be found in the emitted CO_2 and in the net electricity outputs. These cause the difference in outputs.

IS 1/2/3/4HR: These spreadsheets calculate the performance of intermediate storage in connection with a 100% capture plant. To calculate the intermediate storage various steps need to be undertaken; first the lowest prices during the low load profile will have to be identified. Secondly the highest prices of electricity during the high load profile are identified. The first low price is identified as the stripping phase and the high price is denoted as an absorption phase. These prior denotations of stripping and absorption are found the spreadsheet adjusted Electricity price (Adj EP). Below the method to identify the lowest price and highest price are illustrated with the use of 1HR storage.

Identification of the lowest price during the low load profile requires two important known values: In which column the minimum value can be found and the number of the row. The first table shows the electricity prices for the hours in which the low load profile applies. The second table below shows the result for 1HR storage and the minimum value is the next lowest. This is used to define the second lowest value and the second hour of stripping.

AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK
	Low Load Profile (Stripping Phase)									
	28	29	30	31	32	33	34			
PRICES	Hour 01	Hour 02	Hour 03	Hour 04	Hour 05	Hour 06	Hour 24	MIN	Min Hour	ROW#
1-jan-05	€ 42,26	€ 38,40	€ 35,63	€ 21,52	€ 18,89	€ 19,92	€ 10,76	€ 10,76	34	4
2-jan-05	€ 18,30	€ 5,08	€ 3,07	€ 0,01	€ 0,01	€ 0,01	€ 16,22	€ 0,01	31	5
3-jan-05	€ 12,59	€ 10,76	€ 1,98	€ 0,54	€ 1,25	€ 1,32	€ 31,25	€ 0,54	31	6
4-jan-05	€ 20,45	€ 18,79	€ 16,68	€ 14,53	€ 14,32	€ 15,27	€ 30,33	€ 14,32	32	7
5-jan-05	€ 26,52	€ 24,55	€ 21,38	€ 18,55	€ 18,23	€ 22,66	€ 29,85	€ 18,23	32	8
6-jan-05	€ 26,04	€ 24,21	€ 20,90	€ 18,08	€ 17,22	€ 20,77	€ 26,61	€ 17,22	32	9
7-jan-05	€ 21,91	€ 18,67	€ 16,34	€ 13,67	€ 12,91	€ 15,38	€ 25,38	€ 12,91	32	10
8-jan-05	€ 23,27	€ 17,41	€ 14,85	€ 11,84	€ 10,71	€ 13,99	€ 24,39	€ 10,71	32	11
9-jan-05	€ 32,29	€ 22,96	€ 15,07	€ 9,19	€ 8,60	€ 8,62	€ 27,98	€ 8,60	32	12

AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV
	1 Hr Stripping								
	40	41	42	43	44	45	46		
PRICES	Hour 01	Hour 02	Hour 03	Hour 04	Hour 05	Hour 06	Hour 24	Min Hour	ROW#
1-jan-05	€ 42,26	€ 38,40	€ 35,63	€ 21,52	€ 18,89	€ 19,92	STRIP	44	4
2-jan-05	€ 18,30	€ 5,08	€ 3,07	STRIP	€ 0,01	€ 0,01	€ 16,22	44	5
3-jan-05	€ 12,59	€ 10,76	€ 1,98	STRIP	€ 1,25	€ 1,32	€ 31,25	44	6
4-jan-05	€ 20,45	€ 18,79	€ 16,68	€ 14,53	STRIP	€ 15,27	€ 30,33	43	7
5-jan-05	€ 26,52	€ 24,55	€ 21,38	€ 18,55	STRIP	€ 22,66	€ 29,85	43	8
6-jan-05	€ 26,04	€ 24,21	€ 20,90	€ 18,08	STRIP	€ 20,77	€ 26,61	43	9
7-jan-05	€ 21,91	€ 18,67	€ 16,34	€ 13,67	STRIP	€ 15,38	€ 25,38	43	10
8-jan-05	€ 23,27	€ 17,41	€ 14,85	€ 11,84	STRIP	€ 13,99	€ 24,39	43	11
9-jan-05	€ 32,29	€ 22,96	€ 15,07	€ 9,19	STRIP	€ 8,62	€ 27,98	45	12

In the first table, the first minimum value (AI) is found and the column in which it (AJ) can be found. In the spreadsheet column 34 was defined as the lowest and the following coding was used.

To find first minimum value =MATCH(MIN(AB4:AH4);AB4:AH4;0)+27, the value 27 is added to ensure the right column is denoted. The coding is used for every row in the dataset. The coding to find the row is simple (ROW(range)). Using these two known the cell that has the lowest can be identified and changed to "STRIP". The second table shows that this at hour 24 on the first day. The coding to change the cell is:

Change cell into "STRIP" if lowest =IF(ROW(AB4)=$AK4*AND(COLUMN(AB4)=$AJ4);"STRIP";AB4)

This process can be repeated for 2, 3, and 4 hours of stripping. Just use the new table as the starting point for the next. In the second table the new lowest column has been identified (column 44), and so on.

For the absorption phase similar coding is used. However, where stripping phase looks for the minimum in hour 24 till 6; absorption phase looks for the highest (MAX function) during the remaining hours. Furthermore it changes the cell to "ABSORP".

To calculate the performance of the intermediate storage the following coding is used. These calculations can be found in the tabs (1HR, etc). In each HR tab the electricity prices, as shown in the previous depicted tables, are tabled again to show when "STRIP" or "ABSORP" occurs. Then the following coding can be used.

=(IF(B4="ADSORB";'CAP 100%'!B4+EXTRA_E_IS*'Adj EP'!B4;IF(B4="STRIP";'CAP 100%'!B4-EXTRA_E_IS * COE_IS_1HR;'CAP 100%'!B4)))

Where,   EXTRA_E_IS   = Additional electricity to be sold

          COE_IS_1HR   = The cost of electricity for the plant with intermediate storage
                              (See inputs for exact value)

Note – for the absorption phase the actual high electricity prices are used whereas during the stripping phase a fixed value for electricity price is used. This value is higher than the lowest electricity prices but it is assumed that the electricity plant will use its own produced electricity rather than buy from the market. For the other hours the coding is similar but the value for COE_IS_1HR changes. Again, these are operational performance calculations so no capital costs are yet included. In the next section the documented outputs are presented together with the simulation runs.

B.4 Outputs & Simulation Runs

The outputs are predefined by the author as they are changed through the use of a Macro. The macro changes the price for CO_2 between simulation runs and copy/pastes the outputs in a large output table. This large output table is then re-tabled in the results tab in clearly marked tables. The coding used for the macro is shown below:

```
Sub CO2_PRICE_VAR()
' Macro recorded 20-5-2011 by verbaanm
'
For i = 10 To 76
        Cells(i, 1).Select
        Selection.Copy
        Sheets("INPUT ALL").Select
        Range("$B$6").Select
        ActiveSheet.Paste
        Sheets("OUTPUT ALL").Select

        Range("B5:AK5").Select
        Application.CutCopyMode = False
        Selection.Copy
        Cells(i, 2).Select
        Selection.PasteSpecial Paste:=xlPasteValues,
        Operation:=xlNone, SkipBlanks _:=False,
        Transpose:=False
Next i
End Sub
```

Once the inputs have been entered to satisfaction a model simulation run can begin. A button in the output spreadsheet with the name "UPDATE" can be pressed to initiate the macro and the spreadsheet will be updated using the new input values. Once the new outputs have been calculated the model can start to use these values to calculate the Net Present Values (NPV) and the Cost Benefit Ratios. The NPV calculations use the average annual operational income to be discounted against the capital costs of the configuration under investigation.

The following tabs will be used for the interpretation and adaptation of the outputs.

The tab S.A. is used for the sensitivity analysis of the model. It tables specific indicators that are strongly dependent on the inputs of the model. The scenario results refer to the changing of the electricity price factors and comparing them with each other. The three following tabs are graphs that show the NPV/CBR graphs of each FOM under a different electricity price factor and at varying CO_2 prices. The last Tab is an empty spreadsheet but indicates what the next tabs (Pink) are; i.e. they are graphical representations of the results tab.

The graphs that the model creates are:

- OP Cap OFF   = The operational performance of a coal plant with capture OFF
- OP Cap ON   = The operational performance of a coal plant with capture ON
- CO_2 Costs   = The costs endured by the price of CO_2 per FOM
- OP Cap ONorOFF   = The operational performance of a coal plant with capture ONorOFF
- %ON   = Utility of the capture plant at a different CO_2 prices
- OP IS   = The operational performance of intermediate storage
- IS vs. ON Day   = The daily operational performance compared to Cap OFF and CAP ON
- NPV NO-ON   = NPV comparison between a coal plant with / without capture plant
- NPV ONorOFF   = NPV of the FOM ONorOFF compared to the previous graph
- CBR FOMs   = All FOMs in one graph compared on their individual CBR

This concludes the model manual. In general the model is easy to use but care must be taken when filling in inputs; make sure that units are those as shown in the tables. Avoid changing the equations in the calculation tables unless certain about the effects. Finally, the model is unprotected to ensure open en accessible information for future modelers using this model. A final note from the author: this model is based on assumption found in the report but aren't made explicit in the model; hence, only use the model after having read the report.

Appendix C Scientific Article

Flexible Operating Mechanisms for Post Combustion Capture Plants

Reducing Obstacles for Coal Fired Power Plants

to Operate Flexible Capture

Marinus Verbaan – August 2011

Written for Elsevier Energy Policy

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Abstract

Coal-fired power plants are one of the main sources of anthropogenic emissions of carbon dioxide (CO_2). Furthermore, they are under pressure to curb them in order to ensure continuity of operations and aid in the reduction of the greenhouse effect. Carbon Capture and Storage (CCS) is touted by the IEA and IPCC as a vital mitigation tool. Coal fired power plants should invest in capture technologies (accounting for 80% of CCS costs); post combustion capture is regarded as mature and can be retrofitted to existing coal plants. Furthermore, capture of emissions ensures energy security through elongated coal usage. However, at present, investment in this technology has been unenthusiastic and sluggish. This inaction calls into question the current institutional framework with its main driving force, the EU ETS. Numerous studies have taken place involving the necessity of CCS, i.e. the value chain, institutional frameworks, markets and its qualities & flaws; nonetheless there is a lack in knowledge on how coal power plant owners/operators can be incentivized to be first movers. This paper identifies the obstacles coal-fired power plants with capture await and recommends how these could be reduced and possibly avoided. This article establishes that employing Flexible Operating Mechanisms (FOMs) will reduce the financial burden of capture, however future regulatory, institutional, market and contractual obstacles could arise that negate this benefit. The structure of this paper is the following; the first part (A) will present the flexible operating mechanisms (FOMs) and the second part (B) will identify institutional and governance obstacles. The aim of this article is to shed light onto these obstacles and recommend possible approach to reduce these obstacles.

Introduction

Anthropogenic emissions of greenhouse gases (GHG) such as Carbon dioxide (CO_2) to the atmosphere are expected to cause significant global climate change (IPPC, 2001). The most noteworthy anthropogenic greenhouse gas is CO_2. CO2 is primarily produced by the combustion of fossil fuels; presently, more than 80% of global energy needs are provided by fossil fuels. Coal fired power plants account for 60% of the CO_2 emissions of all power generation (IEA, 2003). In order to reduce these emissions to the atmosphere several global initiatives have been or are being committed too; starting with the Kyoto protocol in 1997 and recently attempts were made in Copenhagen 2009, Denmark and Cancun 2010, Mexico. However, reaching a consensus has been problematic at best. Measures, such as increasing renewable fuel sources or improving efficiencies, will reduce emissions but a rapid shift from fossil fuels could cause severe

disruption to global economic growth (Davison, 2006). With the global primary energy demand about to soar, despite efforts to increase the share of renewable sources in the overall energy mix, fossil fuels will remain the most important sources of energy supply in the foreseeable future (Goldthau, 2007).

Experts in the fields of climate and energy agree that CCS is an invaluable asset to reduce CO_2 emissions. Furthermore CCS features prominently in almost every blueprint to limit CO_2 emissions until 2050 (IEA, 2008a; IPPC 2007). CCS is not only supported by the scientific community, it has also received vast interest from world leaders. Especially world leaders from heavily fossil fuel based economies believe in secure (coal based) electricity generation (World Economic Forum, 2010). Furthermore the focus on CCS may grow even more as the cost of mitigation continues to increase as society postpones action (Stephens et al., 2006).

Despite the debate whether CCS ought to occur, investment in fossil fuel instead of renewable technology, it is assumed that CCS will be integral to the emission reduction portfolio of many nations. Regardless of the urgency to demonstrate CCS technologies (IEA/CSLF, 2010) and continuously increasing funding, no fully integrated power plants with CCS have yet been built on a commercial scale (de Coninck et al, 2009). Hence, the key concern is how CCS could be implemented on a large scale that is both economically viable and can significantly reduce CO_2 emissions.

This article proposes and assumes that CCS shall ensue and that the initial focus should be on reducing costs for the capture process. Estimations, preformed by the IPCC (2007) and IEA (2003), contribute 70-80% of the total CCS cost to the capture of CO_2. There are three general techniques for the capture of CO_2 during energy production from fossil fuels; oxyfuel, pre- and post combustion capture. Even though, oxy-fuel and pre-combustion capture may prove to have lower capital, operational and energy costs, post combustion capture's ability to be retrofitted to existing coal-fired facilities may be very important if coal-based plants are to remain in service throughout their useful life (Metz, 2005). Should society desire a hasty deployment of CCS; then post combustion capture at coal-fired power plants is an attractive option. Here forth, capture will refer to post combustion capture.

Existing coal plants are, in relation to other power generation methods, highly inflexible (lambertz, 2010). The operational environment is rapidly changing for coal plants; the increase of renewable energy sources, emissions regulations and increasing fuel prices demand more flexibility. These increases have a strong impact on the variable costs to generate electricity and could threaten its position in the merit order. Additionally, coal could lose its current base load generation position to natural gas, nuclear and renewable energy and therefore be pushed to supply more variable demand.

The state-of-the-art coal plants are increasingly capable of integrating flexibility into their operating portfolio. However, most contemporary coal-fired power plants are built to run as base-load installations; and therefore aren't designed with these additional flexibility options. Furthermore, the selection for post combustion capture was based upon its capability to add-on to existing power plants (retrofit capability). Even though, ultra modern coal plants can integrate more flexibility, most plants that capture will be used for are older, with little to no flexibility.

The inclusion of capture to a coal plant creates a negative externality for the cost of electricity (€/MWh) and the cost of avoided CO_2 (€/ton CO_2); furthermore, the technological integration of both processes could reduce flexibility even more and increase operational complexity. However, initial analysis suggests that this may not be the case for post combustion capture plants (IEA GHG R&D Program, 2004). Moreover, flexibility could be increased by the capture plant; although at an energy penalty. For instance, a coal plant with capture could vary its output to the grid by manipulation of the capture process; i.e. by turning the capture operation from full to zero load. In effect, the capture plant allows a coal plant operator with capture to provide auxiliary services to the grid (Chalmers, 2007). These flexible operations of a capture plant are referred to as Flexible Operating Mechanisms (FOMs).

The aim of this article is two-fold: a) to describe and discuss the FOMs and their impact on the performance of the coal plant with capture and b) identify institutional and governance obstacles that can limit the effectiveness of these FOMs; moreover, how these can be reduced or even negated.

The research questions addressed below is that of a coal plant operator that has a mechanism that could potentially reduce costs and improves overall flexibility of its operation.

- Which FOMs will increase flexibility and operational performance?
- Which obstacles can be identified limit the effectiveness of flexible operation?
- How could these obstacles be reduced or even negated?

The paper concludes by providing the most urgent challenges for FOMs to be applied in the 'real' world.

Flexible Operating Mechanisms (FOMs)

Several authors have proposed flexible operations to reduce the financial burden inherent with capture (e.g. Gibbens and Chalmers, 2007; Lucquiaud and Gibbens, 2008; Cohen, 2009). Additionally, a capture plant's ability to increase flexibility for coal plants on a operational level interacting with the grid (Chalmers, 2010). These papers discuss the technical requirements, behavior and operational performance. Three types of flexible operating mechanisms have been identified;

(i) **Capture ONorOFF** refers to the ability to switch between full (ON) and zero load (OFF). Capture OFF can have two meanings; either switching the capture ON mode to a hot or a cold state. The hot state refers to a standby mode; flue gas from the coal plant is emitted directly to the atmosphere, absorber and strippers halt function but the reboiler remains at rated pressure and temperature. The other capture OFF mode is a transition to a cold state; the same as a hot state however, the reboiler heating is also turned off. The difference between the two states is the start-up / shut-down times. For quick switching (hourly) between ON and OFF, a hot state is preferred; for longer intervals (more than a 12 hours) a cold state is deemed more economic.

(ii) **Partial Capture** refers to the scale of the capture plant in relation to the feeding coal plant. For instance, a 40% partial capture plant in conjunction with a 1000MW coal-fired power plant is defacto a 400MW

capture plant. Technically, not a Flexible Operating Mechanism, however on an operational level (operational costs) it is at par with a 100% capture plant running at 40% load capacity. In relation to the capture ONorOFF, this FOM requires more than just operational foresight and planning. The decision to invest and construct a smaller capacity capture plant will need to be made near the beginning of the design phase.

(iii) **Intermediate Storage** aims to maximize the income from electricity by turning off the stripper at the moment electricity price peak. During this time the rich solvent is stored in a tank, while lean solvent is retrieved from a different storage. Intermediate storage can be done with different time frames; this article will focus on a maximum of 4 hour storage and a minimum of 1 hour. At high electricity prices the capture process will halt stripping and compression to gain extra electricity (from the energy penalty) to be sold. When the coal plants is at low load (night time) more

stripping and compression will be needed; i.e. the capacity of the capture plant will have to be designed to cope with this additional rich solvent. However, as the maximum storage time is 4 hours and the low load period lasts 7 hours it is assumed that the surplus CO_2, in relation to "normal" operation, can be completed in this time frame

The FOMs each provide (an) operational degree of freedom for the operator. The capability to increase electrical output to the grid by switching between zero and full load for capture is valuable. Coal plants can, employ the capture ONorOFF FOM, to provide auxiliary services to the grid. This can include load following, provide back-up supply and generally the ability to act on market changes and demand. The advantages and disadvantages of the FOMs together with requirements as shown in table 1.

Table 1 Advantages/disadvantage and requirements per Flexible Operating Mechanism

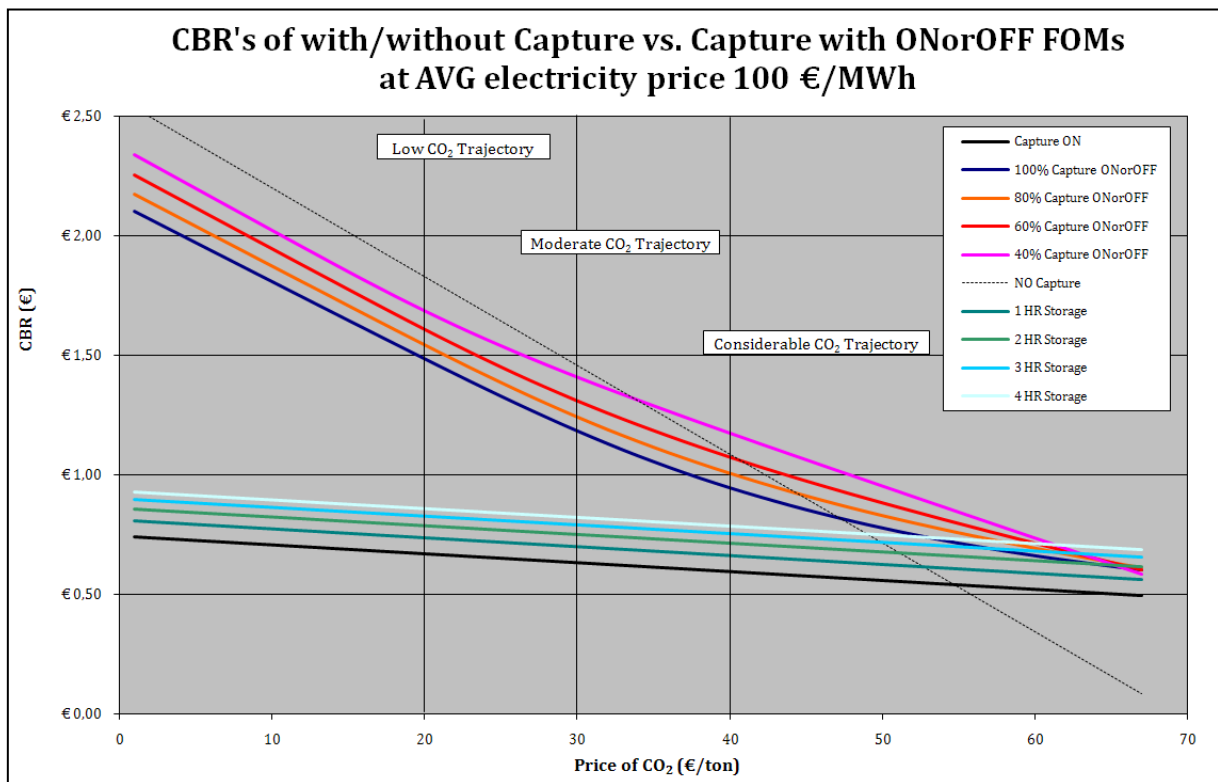| Flexible Operating Mechanism	Advantages	Disadvantages	Additional Requirements
Business as Usual (BAU) – No Capture	▪ No change in operations	▪ Continued incurred CO_2 costs without minimizing options	▪ None
Capture ON or OFF	▪ Avoid energy penalty at favorable prices, i.e. sell more electricity ▪ Cheap and effortless to apply to current process	▪ CO_2 costs will be incurred at times capture is off,	▪ Valve to vent flue gas prior to capture
Partial Capture (80, 60 & 40%)	▪ Become operational beneficial at lower CO_2 prices ▪ Faster investment payback time at lower CO_2 prices	▪ Early design decision ▪ Could become obsolete at a given CO_2 price requiring additional capacity	▪ Redesign of the capture plant prior to construction
Intermediate Storage (1,2,3 & 4 Hrs)	▪ Gain extra income at high electricity prices ▪ Keeps capture rate of 90% ▪ No extra CO_2 emissions	▪ Additional land space is required ▪ Increase stripper and compression capacity	▪ Storage tanks and land space ▪ Additional Solvent

Figure 1 CBR analysis of the FOMs at an average electricity price of 100 €/MWh.

The analysis presented in table 1 suggests that FOMs will provide beneficial attributes to a coal plant with capture. A techno-economic performance of the FOMs has shown that FOMs improves a reference business case (coal plant with capture). Furthermore, the benefits of the flexible operation outweighs the investments costs if electricity and CO_2 prices are favorable; a model was developed by the author, in conjunction with TNO Separation Technology (Delft, Netherlands), to calculate the hourly operational performance with hourly electricity prices at a given CO_2 price, during the period 2005-2008. This electricity price data set was provided by the APX through the Utrecht Copernicus Institute. The annual operational income is, together with the initial capital costs, discounted at an 8% interest rate in a NPV. Under initial conditions, the average electricity price over the whole data set was found to be 56-57€/MWh, all FOMs had a negative NPV.

However, the FOMs consequently had higher NPV's than the reference plant with capture. To examine the cost benefit ratio the present value of the FOMs were calculated (NPV divided by the initial capital investment costs).

In order to examine, at which electricity and CO_2 prices the FOMs would return a positive business case and outperform the reference plant without capture price, various trajectories were established. From this analysis the conditions needed to provide a positive business case (CBR>1) were found at an average electricity price of 100 €$_{2008}$/MWh and CO_2 prices between the ranges of 35-45 €$_{2008}$/ton CO_2. The results of the cost benefit ratios are illustrated in figure 1. When CO_2 price reach €50 per ton all the FOMs have a lower CBR than 1; i.e. every euro invested will return less than 1 euro.

Without going into the discussion about the actual numerical outcome of each FOM a trend can be established. Utilizing the ONorOFF FOM will improve the techno-economic business case in relation to a reference plant with capture. Moreover, when prices for CO_2 reach higher than

±25€/ton CO_2 then the 40% Capture ONorOFF configuration out performs both the reference with and without capture. Another, observation found, using the FOMs Model, was the positive influence of intermediate storage on the overall performance of a reference plant with capture.

Although, the combination of a smaller capture capacity and employing both ONorOFF and intermediate storage, wasn't analyzed; it is expected to perform even better than with no intermediate storage. A critique on this model is that it doesn't account for opportunity costs.

Understanding, that the FOMs provide both a reduction in the costs of capture and add flexibility to operations of a coal plant doesn't mean that these will be implemented. The techno-economic analysis and exploration of the flexibilities is only half the story. In the next part of this paper the institutional and governance obstacles/challenges are presented and discussed. Additionally, recommendations will be provided how these obstacles could be overcome.

Obstacle Identification

The previous section outlines the value of capture with FOMs in relation to those without. Furthermore, it presents that FOMs do in fact improve the business case for coal plants with capture. However, it fails to address the higher level questions. Is the application of FOMs feasible in a 'real' world setting? In this section the possible obstacles to implementing these flexible operations will be investigated. This article will identify the obstacles that future regulations, institutions and contractual obligations pose.

These 'real' world settings could reduce the value of a FOM or even remove it. Different aspects that could reduce the value of a FOM can be found within one of these three fields:

- **Regulatory:** uncertainty pertaining to future CO_2 (supra) national emission laws in both its formulation and execution.

- **Governance:** governing institutions could impose demands on the CCS system to maintain operational status. It also has the means to provide incentives.

- **Markets:** Competing with other electricity producers and operate within a CO_2 market.

- **Contractual:** agreements between private and/or public partners within the CCS network.

- **Public Acceptance:** The public opinion can drive policy changes and therefore impact FOMs.

The current institutional regime is inadequate for a full scale CCS system (Zakkour, 2007); therefore, its stands to reason that a new institutional regime will need to be installed to ensure that mitigation policies are properly formulated and executed. This includes monitoring of the system as a whole and the individual user. Understandably, the complete roll-out of CCS will not happen in a fortnight thus intermediary steps will most likely happen. The difficulty with an iterative process is that new entries (more CO_2 sources added to the existing system) could require adaptations or worse, cause the system to fail.

Coal-fired power plant operators and owners are interested in continued operation and profitability. Knowing that continued operation will be in a CO_2 market; either the existing EU Emission Trading Scheme (ETS) or a derivative of it in the future, the plant will make

losses on CO_2 emissions. Currently the price for CO_2 is too low for them to warrant investment in capture technologies and buying emission credits is preferred (E3G, 2008). Nonetheless, most believe that the price will rise in the future and are looking at means to reduce investment, operation and maintenance costs. Especially for coal-fired plants CCS could have negative effects on their current business model as previously described. In the following sections the 4 main obstacles (regulation, governance, markets and contractual) are defined. Additionally, the effect of public acceptance is discussed.

Governance & Regulation Obstacles

Currently CCS, on an EU level, is guided by a number of different pieces of legislation; the CCS Directive; the Environmental Liabilities Directive (ELD); the European Trading Scheme Directive (ETS) and the Integrated Pollution Prevention and Control Directive (IPPC) (EU commission, 2009).

This progression in decisions by the EU provides a possible direction of likely future operating environments for coal power plants. CCS will come to pass and coal power plants will have to comply and build capture plants. However, the decision to invest in a capture plant can still be postponed. As long as CO_2 prices remain at current levels the driving force to build is negligible; i.e. fossil fuel plants will pay the tax. The current governance model is to use the EU ETS market to drive the reduction of emissions. The regulations and directives described above are to promote or instigate investment in capture technologies and are therefore beneficial for the successful application of the FOMs. However, some regulations that are proposed could limit the functionality of the FOMs. One of these

regulations is the European experience with SO_x and NO_x emissions under the large combustion plant directive (LCPD). These employ an Emissions Performance Standard (EPS); limit emissions to the atmosphere to a certain degree (Wartmann et al, 2009). Should these restrictions be applied to CO_2 then all FOMs except intermediate storage would function. Even if the limitation of emissions is 50% of annual emissions, the effectively of the application of the FOMs (except intermediate storage) is reduced. Operators will have to estimate when turning the capture OFF is valuable and remember an annual quota.

The uncertainty which governance structure and regulatory framework will be used is the greatest obstacle. Without clear 'rules of the game' it will hard to state exactly which structure or framework will impact the future performance of the FOMs. However, hedging against these risks is always a smart move. In this respect the intermediate storage FOM has an advantage in respect to switching ONorOFF. From a perspective of an investor interested in adding capture to a coal plant, a clear and upfront understanding of the possible future governance and regulatory framework is essential. Furthermore, a less strict policy towards capture rates and quotas (i.e. allowing FOMs) could expedite investor decision making.

Markets & Contractual Obstacles

The period in which large scale CCS will most likely come to fruition (authors assumption) will be around 2020-2030. Assuming that the APX is still in use and all electricity will be sold through this market the following changes can be expected; through increase renewable the prices will be generally lower but higher fluctuations will ensue. The intermittency of renewable

causes these fluctuations; it's in these periods that electricity will need to be generated through other means. Initially, prior to the nuclear disasters in Japan 2011, nuclear power was opted to provide additional electricity. However, favorable attitude towards nuclear has decreased and therefore fossil fuels will need to cover the gap in supply. This means that coal power plants will have to compete with natural gas-fired power plants. Both gas and coal will have to pay the taxes for their emissions or capture them. The difference in costs favor coal to be the main base load supplier; nonetheless, natural gas is becoming more competitive and its capability to quickly ramp up and down to give it an edge in the auxiliary markets. The FOMs will provide coal power plants with increased flexibility by switching between ONorOFF. Nevertheless, the action to switch off or on will dependent also on the prices of CO_2.

The price of CO_2 is set by the EU ETS. This market has been setup with the goal to curb emissions and work on the principle 'polluter pays'. Currently, the price for CO_2 is 15-16 €/ton and this is too low to warrant any capture investment; i.e. paying the tax is less costly. In phase III the EU ETS will decrease its credits on the market by 1.74% and therefore create shortages in supply with an expected rise in demand should increase the price for CO_2. Consequently, investment in capture technologies and a whole CCS becomes more feasible. By applying FOMs the investment in capture technologies at power plants could be expedited; however, this will only hold true if CO_2 prices will continue to rise / stay stable at higher prices. Through market imperfections and failure this market could collapse; as happened at the end of phase I, when it was discovered that too many credits had been

issued through the National Allocation plans (NAP). Therefore, monitoring of emissions will need to continue to ensure a functioning market; should this not happen and the market fail yet again strong changes could be expected; for instance, stronger regulation and closer institutional oversight to maintain a working CO_2 market. The actor most likely to maintain the system oversight is a TSO. Similar to the electricity grid TSO a CCS TSO will need to monitor flows within the system and the emissions by other sources.

Both the electricity and CO_2 markets will undergo several changes that will influence its current character. This uncertainty, how prices will change, causes great anxiety amongst investors and operators alike. Also the consumer behavior will change over the coming years; more and more consumers are opting for 'green' electricity and actively trying to reduce their carbon footprint. This would suggest more renewable to be built and this seems to be the case; however, this provides challenges for the TSO. The introduction of more intermittent sources, such as wind and solar, reduces the overall stability of the grid. Therefore, it is expected that fossil fuels, in absence of nuclear, will have to provide these services to balance demand and supply.

How do these changes in the market and institutions impact the FOMs? The answer to this question is not straightforward; there are market changes that would benefit the FOMs capability to perform and there are those that reduce the functionality of them. These changes in the markets impact the FOMs on an economic level; the price of electricity and CO_2 influence the value of the FOMs. Furthermore, institutional changes impact FOMs on their capability to function; i.e. will turning OFF the capture be

allowed by the CCS TSO? Moreover, does turning OFF the capture plant bring the whole value chain of CCS in jeopardy? One could imagine that transport parties will not be in favor of the ONorOFF FOM as it reduces its transport capability and income; should capture plants share the profits from turning OFF or temporary storage with other parts of the CCS value chain? These questions lead to the next section where more of these issues are discussed. In conclusion, the recommendation will be to analyze how electricity and CO_2 markets will change, both in value and behavior, and examine how the FOMs would function then.

Currently, coal power plants sell their electricity either through bilateral contract and/or on the APX. The other type of trading the coal power plants does is through the use of bilateral contracts with large private users; i.e. aluminum production, production industry and other large users. These users need reliable energy sources that can supply without fail; for this reason the switch to intermittent sources is less likely in the short to medium timeframe. These contracts consist mainly of fixed tariff for a certain amount of electricity at a certain time schedule. Although, newer bilateral contracts include the possibility to switch between spot market prices and those used by the power plant supplier, the impact of the FOMs is similar. By the application of the FOM a coal plant can compete with the spot market. For instance, if the spot market prices are high, the coal plant will turn off its capture plant and thus produce more electricity that it can sell at those prices. However, the coal plant operator could also use this gain in profit to compete with other suppliers; i.e. lower prices to be a more attractive trading partner. Again, these are not researched statements but recommendations for

future work. It still will have to be analyzed if the FOMs could provide this competitive edge.

Due to uncertainty of the future development of the electricity and CO_2 prices hard statements about the FOMs impact of contracting is uncertain too. Nonetheless, one could imagine that contracts with other members in the CCS network will have an impact on the value and functionality of the FOMs. One example, that has been described previously, is the contracting with transport parties; can the capture plant be turned off at will or will this impact the downstream function of CCS? These issues will have to be negotiated prior to design and construction. These contracts between parties within a CCS network will have to be clear and well understood; leaving no room for misinterpretation that could lead to the whole system failing. Initially, turning the capture plant ONorOFF could not happen as the system is not robust enough; however, should the system integrate more suppliers of CO_2 then FOMs could be used by a limited number of parties, including coal power plants, more freely. Albeit, these are speculations and will have to be examined in more detail in future research

Public Acceptance

Public acceptance has shown to have a strong impact in the early stages of CCS demonstration projects; Barendrecht in 2010 provides a clear case that public opinion can halt projects even before they begin. The NUMBY (Not Under My Back Yard) principle applies here. Can public acceptance reduce the effectiveness of FOMs is an interesting question. One could imagine that public opinion on the emission of CO_2 is hardened and subsequently influence policy. This could directly affect the regulators to develop stricter emissions laws;

therefore, the option to turn capture ONorOFF is reduced or even lost. Intermediate Storage will be less impacted by public opinion as it doesn`t create higher emission through its use.

Conclusions

FOMs present coal plants with higher degrees of freedom and flexibility than before. Coal power plant operators will also have the possibility to act strategically on the basis of CO_2 and electricity prices. These advantages could prove valuable to expedite the decision to invest in capture. However, besides the positive effect of FOMs on the techno-economic business case other obstacles can reduce the affectivity of the FOMs. In short these obstacles are: regulatory demands on the emissions of CO_2, uncertainty about governance structure that will monitor the CCS network, market changes and demands, contractual conflicts with other parties in the CCS system and public acceptance influencing policy.

From an operators perspective a lenient regulation is preferred. This will allow the operator to maintain its 'new found' flexibility and reduce costs of capture. Also understanding the development of the markets in which a coal plant operates will define how well it can operate within it. Furthermore, contractual obligations between parties in the CCS needs to investigated further on a technical level; can a capture plant turn off its capture without disturbing transport operations. Finally, realize that public acceptance is a strong policy driving force.

The level of impact these obstacles / challenges have on FOMs is still uncertain but identification of which obstacles is the first step to research means to reduce or negate these obstacles. One of the FOMs, intermediate storage seems to be least affected by the obstacles; nonetheless, like the other FOMs the effect on other parts of the CCS system will have to studied in greater detail.

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Appendix D Green Light Assessment Form

TPM faculty MSc thesis assessment form

First version ('green light form')

Student first name   :**Marinus**   **last name**   :**Verbaan**

Student number   :**1095404**

Please fill out your comments in TEXT
- give feedback and
- suggestions to improve

1. Final thesis content
- for self-evaluation purpose
Thank you!

• *ambition level* - scope and complexity of problem - complexity of research field (policy-wise, organization-wise, etc.)	Good. The attempted modeling of the techno-economic performance of CCS has not been done before and is new in the literature. Focus on Tech-econ, and less on institutions and governance issues.
• *structure and boundaries* - relevance of aspects presented - balance of attention devoted to aspects - end results (relative to ambition level)	OK. The greenlight version of the report needs to be improved with respect to: systematic introduction, and more clear/concise representation of the relevant results. More attention must be devoted to institutional aspects (in the final chapter).
• *academic level* - application of theories and hypotheses - choice and implementation of methods and techniques - methodological underpinning/reflection - links made with the relevant literature - quality of the argumentation - general validity	Good. Modeling V&V is good. Methodological underpinning is brief. General validity is high. Some additional analysis of results is necessary (e.g. investing vs operations; NPV analysis).
• *Technology, Policy and Management calibre* - interdisciplinary (field of study covered by several sections within the course) - 'TU Delft' calibre - attention paid to multi-actor context - balance between content and process sides - design/recommendations for daily business or (the process of) strategy making	Fair. Strong focus on economic valuation, Reflection and academic paper should capture reflection on institutional issues. Suggestions were made w.r.t. market mechanisms and the embedding of CCS in the larger system, long-term contract prices setting incl. CCS.
• *originality* - own ideas, regeneration or deepening - how it combines with the results of the work of others	High. No such studies are known in literature.
• *usability* - for the client	High.
• *relevance* - societal relevance	High.
• *reflection on the product(s)-* critical judgment underlying research project	OK. More reflection (broader, more free) is necessary.

2. Execution and process

• *work plan* - the plan made - planning as executed	OK.
• *autonomy and own initiative* - content-wise: inventory and selection of theories, methods, literature - organization-wise: initiation of contacts, creating of involvement and support	OK.
• *speed of work*	OK.

3. Scientific paper (only for Msc-SEPAM students who started in or after 03-04)

• *design and structure* - followed guidelines of chosen author and layout (journal, proceedings or records) - title, key words, tables, diagrams, references - structure and length of paper, summary, line of story, conclusions - style, use of English language	Needs to be improved. Is currently somewhat too loose. Suggestions have been made for improvement, in line with improving the reflection chapter of the thesis. English language is good.
• *relevance* - goals, problem definition, research question and hypothesis - scientific argumentation and methodological justification - references and data analysis - scientific relevance - societal relevance - focus on solutions	When recommendations are taken into account, the paper can become of very high relevance. Another paper has been suggested that is definitely publishable comprising a 'summary' of the entire study. This proves relevance of the work done.

Herewith the education administration of the faculty TPM declares that

_____*Marinus Verbaan*_____

has fulfilled all of the course requirements.

Herewith the chairman of the thesis committee declares that

_____*Marinus Verbaan*_____

is capable to complete the thesis within four weeks and to give the final presentation, provided that the discussed corrections meet the requirements.