Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 00 (2013) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

GHGT-11

Reducing the cost of Post Combustion Capture technology for Pulverized Coal Power Plants by flexible operation

Robert C.F. de Kler[a], Marinus Verbaan[b], Earl L.V. Goetheer[a*]

[a] *TNO Leeghwaterstraat 46, 2628 CA Delft, The Netherlands*
[b] *Delft University of Technology, Process and Energy, Leeghwaterstraat 44, 2628 CA Delft, The Netherlands*

Abstract

Currently the low carbon prices, low Spreads and regulatory uncertainties hampers the business cases for coal-fired power plants with post-combustion capture (PCC) in Europe. Improvement of the business case of coal-fired power plants with post combustion capture requires a different approach in terms of operational dispatch and in terms of investment planning. Both items has been assessed using a comprehensive power plant valuation model developed by TNO.

To change the typical base-load production profile of a coal-fired power plant into a more flexible production profile, a Flexible Operating Mechanisms (FOMs) has been developed for PCC.

Based on the results of the techno-economic modeling, FOMs improve the business case. Next to this, FOMs present coal fuelled power plants with additional flexibility. This added flexibility could allow coal plants to provide auxiliary services to the grid and remain competitive in relation to cleaner gas-fired plants. The increase of operational flexibility with FOMs created a significant improvement of the NPV value and, therefore, it is justified to look in much more detail how the operational flexibility of a coal-fired power plant with Carbon Capture can be improved.

Running a power plant with a 100% capture unit at base load will require significant amount financial support to close the gap. Starting with a smaller capture unit reduce the financial risk and could improve the business case of the coal-fired power plant without PCC from a marginal cost point of view. The main reason for this is the increase of flexibility, by switching on/off the capture unit. Next to this, the decision to invest is always affected by the opportunity costs of making a commitment now, and thereby, giving up the option of waiting for improved market condition. Increasing the size of the capture plant in stages enables the investor to manage those opportunity cost much better.

Selection and/or peer-review under responsibility of GHGT

Key words: CO2 capture; Techno-economic evaluation; investment; disptach optimisation

* Corresponding author. Tel.: +312623027059
E-mail address: earl.goetheer@tno.nl.

1. Introduction

With on the EU agenda; the reform of the EU Emission Trading Scheme (ETS), the internal energy market, energy taxation, biofuels, shale gas, carbon capture and storage (CCS) and nuclear energy, it is difficult to guess the future policy. Although CCS has been on the EU-agenda for decades, it has not materialized in large industrial scale EU-demonstration projects yet. According to the GCCSI, "Carbon Capture and Storage (CCS) is happening now and continuing to grow at a strong pace – with dozens of large-scale integrated projects either in operation or under construction". Currently there are eight large-scale projects in operation around the world and a further six projects are under development. Three of these projects have recently commenced in to the construction phase, none of the three are in Europe. \

Nevertheless, companies are undertaking CCS in response to climate policies "license to operate", while this development remains a challenge to achieve a reasonable business case. The EU has an urgent action of going forward making next steps towards the future; this includes the necessary implementation and demonstration of proven CCS technology in the EU energy market. The EU market might need deeper cuts in the ETS system to achieve a sensible Carbon value it would not reduce the financial risk of the first demonstration projects. Nevertheless**,** a rational approach is needed to implement and demonstrate Carbon Capture technology in the power sector.

CCS consists of three main elements; capture, transport and storage. For the power sector, there are three basic systems for capturing the emitted CO_2: post-combustion, pre-combustion, and oxy-fuel combustion capture. Although these options are mainly being developed for the power sector, they could have a wider use. Post-combustion capture offers, in contrast to other capture technologies, the ability to be retrofitted to existing plants. Hence, policy developers have suggested that coal power plants be the first to implement these mitigation technologies.

Niels Bohr allegedly once said: "Prediction is very difficult, especially about the future". Predicting future prices for energy commodities are especially difficult since the tradable forward curves are short lived. Hence, energy companies make strategic investment decisions with respect to constructing a power plant based on various long-term expectations about market conditions, typically defined with a set of price scenarios. On the other hand, an energy company also wants to include the value of strategic decisions with respect to the dispatch of the plant based on short-term observations on market conditions. For example, an energy company will sell its excess power in a day-ahead or real-time market based on prices in those two markets and plant operational conditions. Vice versa, it will decide to buy back power from these two markets when it is cheaper to buy power than to make (generate) it. Consequently, an energy company has multiple make-or-buy options with respect to the future output of a power plant. With the inclusion of the carbon as an additional commodity; strategic investment decision and plant dispatch has become a very complicated task.

Currently the low carbon prices hamper the business cases for coal power plants with post-combustion capture. The focus of this article is to improve the business case of coal-fired power plants by employing Flexible Operating Mechanisms (FOMs). To assess the intrinsic value and option value (flexibility) of a coal-fired power TNO developed a valuation model [1]. Next to this, this article focuses on the investment decision of the Capture Unit in terms of size and timing.

Nomenclature

APX	Amsterdam Power Exchange
ASC	Advanced SuperCritical
BL	Base Load
CAPEX	Capital Expenditures
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CO2	Carbon Dioxide
FOMs	Flexible Operating Mechanisms
OPEX	Operational Expenditures
PCC	Pulverized Coal Cycle
NPV	Nett Present Value
NW	North West (Europe)
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek

2. Methodology

2.1. Flexible Operating Mechanisms for Carbon Capture

The objective of employing Flexible Operating Mechanisms (FOMs) for coal power plants with post combustion capture is to improve the business case and provide plant operators with more flexibility to counteract changes in the market and demand. The operational environment for coal plants is changing; growing fraction of sustainable and renewable sources in the energy mix, public concerns about emissions and global warming intensify and increasing fuel prices. Moreover, if coal plants want to remain operational throughout its technical lifetime, it is expected that coal plants will have to invest in capture technologies. Furthermore, coal power plants with or without capture units will have to compete with gas-fired power plants on the merit order. In addition, coal plants should become more flexible to facilitate the variable demand; however, existing 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. Flexible Operating Mechanisms for the Capture unit are a means for a coal plant to change its operational status to strategically take advantage of high electricity prices and/or low fuel and CO_2 prices; i.e. deviate from the standard operating procedure of always capture at base load conditions. Switching off the Capture Unit, when the spread (S) is high might be an attractive business opportunity for the plant dispatcher. In addition, applying a smaller capacity capture plant in relation to

the coal fired power plant as well as applying the FOMs lowers the marginal generation costs and, therefore, improves its position on the merit order.

The so called “Spread” (S) is the difference between the price of the power output and the costs of the input factors (e.g. fuels). As such, the spread is the contribution margin that a plant operator earns for converting fuels into electrical power. FOM also consider the costs of CO_2 emissions and take the so-called “clean” spreads for the assessment. The spread of coal-fired plants is called “clean dark spread”, the spread of gas-fired power plants “clean spark spread”, see figure 1 for an overview of historical dark spreads in the Netherlands. In general the spreads power plants are defined as the difference between revenues and variable costs of power generation:

$$S = P_e - C_f/\eta_{el} - (\lambda_f - \gamma_p) \cdot C_{co2}$$

Where:

S	is the specific spread of a power plant in € per MWh of produced power
P_e	is the market price of power in €/MWh
C_f	denotes the fuel costs in €/MWh
η_{el}	the electrical efficiency of the condensing plant
λ_f	CO2 emission factor of the fuel used in tons of CO_2 per MWh
γ_p	free allocation of CO_2 certificates for electrical power in tons of CO_2 per MWh
C_{co2}	market price of CO_2 allowances in € per t of CO_2

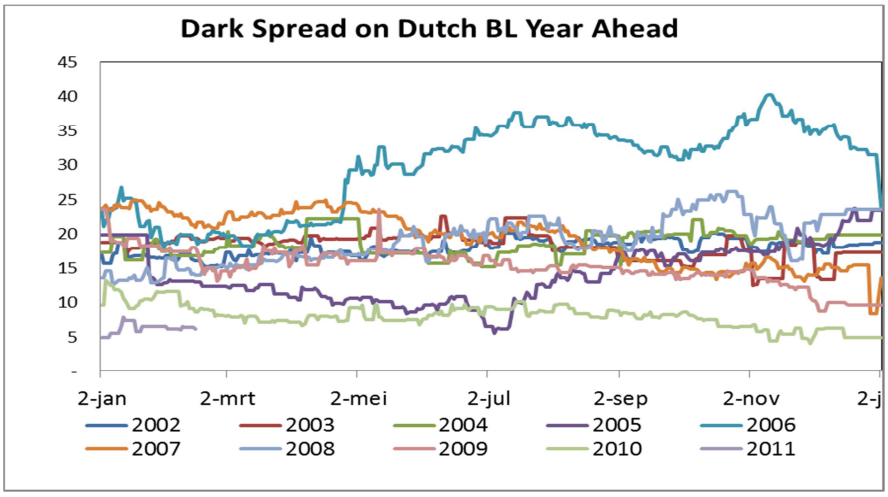

fig. 1 typical Dark Spreads in the Netherlands in €/MWh [4].

2.2. Techno-economic Modeling

To assess the techno-economic performance a detailed valuation modelhas been developed. The model assess the operational performance of the FOMs at different sizes/number of capture plants (pro-rated). The main assumptions and operational performance of the power plant and capture is obtained from the CESAR study [2]. The FOMs model integrates correlated fuel, CO2 [3] and electricity price scenarios [4] to examine the performance of a coal plant with TNO Carbon Capture technology compared to a gas-fired

plant. The Model has been developed to provide fundamental insight in the intrinsic value and option value of the FOMs. The option or flexibility value of a power plant is the difference between the intrinsic value, derived from a static forward price curve (hourly, monthly or something else). The option value is realized by adapting the production profile to changed price scenarios: If spreads turn positive, the plant is switched on. If spreads turn negative, the plant is switched off. With this behavior, profits are added in positive market circumstances, while losses are avoided by stopping the production in negative market circumstances. See figure 2 for the calculation structure and adding up value.

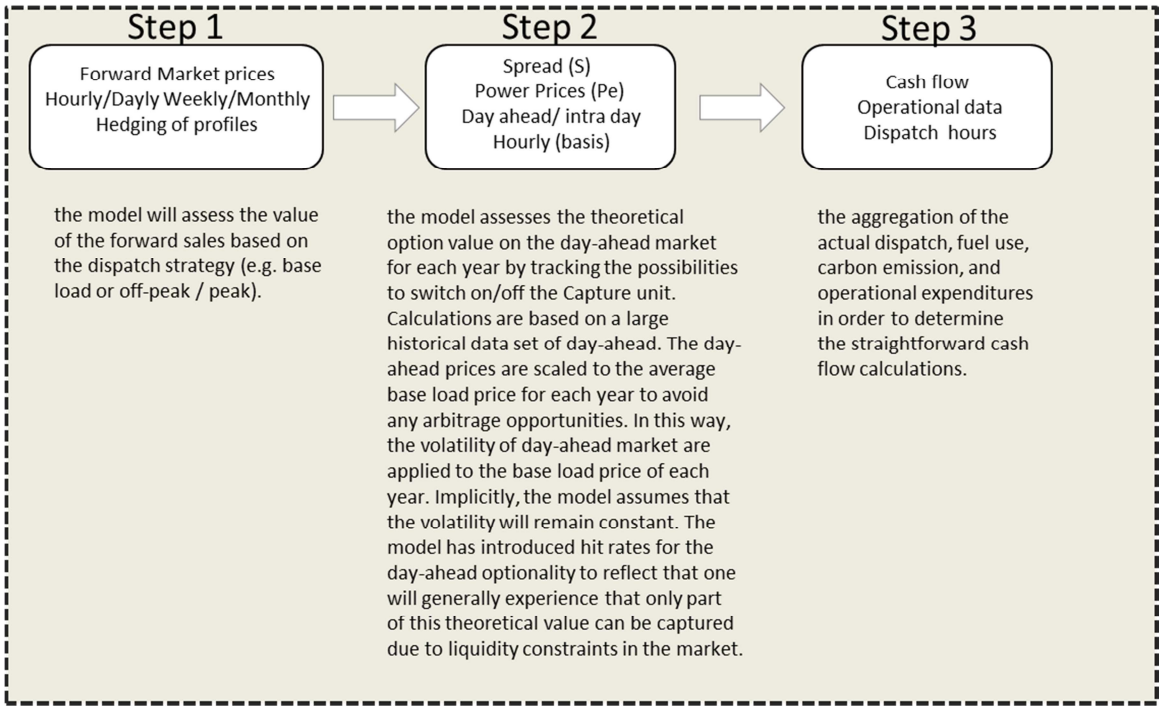

fig. 2 methodology buildup of the plant value

Furthermore, the initial sizing of the Carbon Capture plant has a strong influence on the business case; therefore, different sizes/numbers of the capture plant(s) in relation to the integration with the coal plant have been analyzed whilst employing the FOMs. As such different number of capture plants or sizes of capture plant have been assessed (no-cap, 40%, 60%, 80, 100%). The size of the Carbon Capture unit matters, since the demand of LP-steam is significant and at full size conditions has a massive impact on the Power Plant efficiency, mainly due to the off-design conditions of the steam turbine and LP-steam consumption for stripping the CO2. The decision to invest is always affected by the opportunity costs of making a commitment now, and thereby giving up the option of waiting for improved market condition. Increasing the size of the capture plant in stages gives the investor the opportunity to manage these opportunity costs.

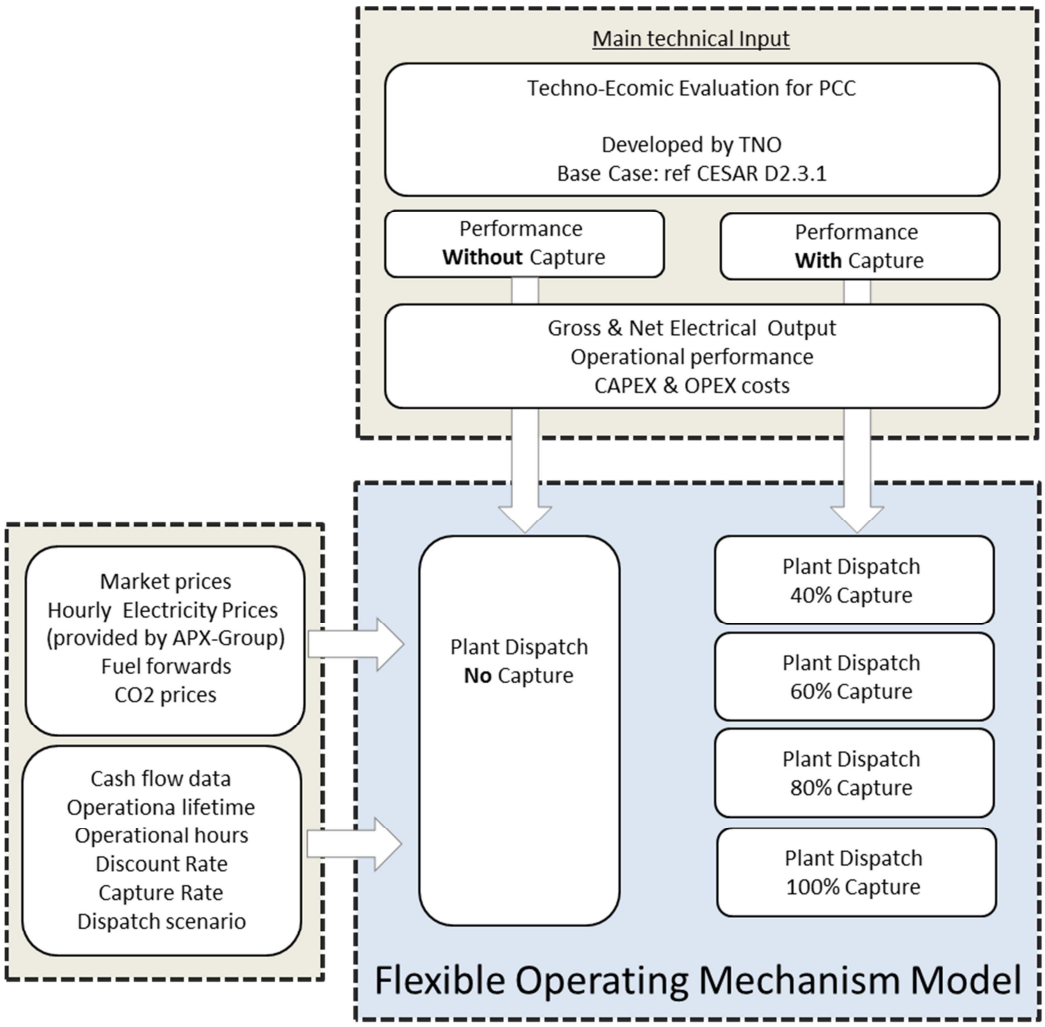

fig. 3 model structure – interdependencies between the models is presented

2.3. Effect of capture at coal power plants on the merit order

The merit order is a way of ranking available sources of energy, especially electrical generation, in ascending order of their short-run marginal costs of production, so that those with the lowest marginal costs are the first ones to be brought online to meet demand, and the plants with the highest marginal costs are the last to be brought on line. Currently, coal power plants operate in the lower marginal costs of production in comparison with gas-fired power generation plants; i.e. provide the base-load generation of

demand. However, the future operational environment for coal-fired power plants will be altered by the introduction of capture. See figure 4.

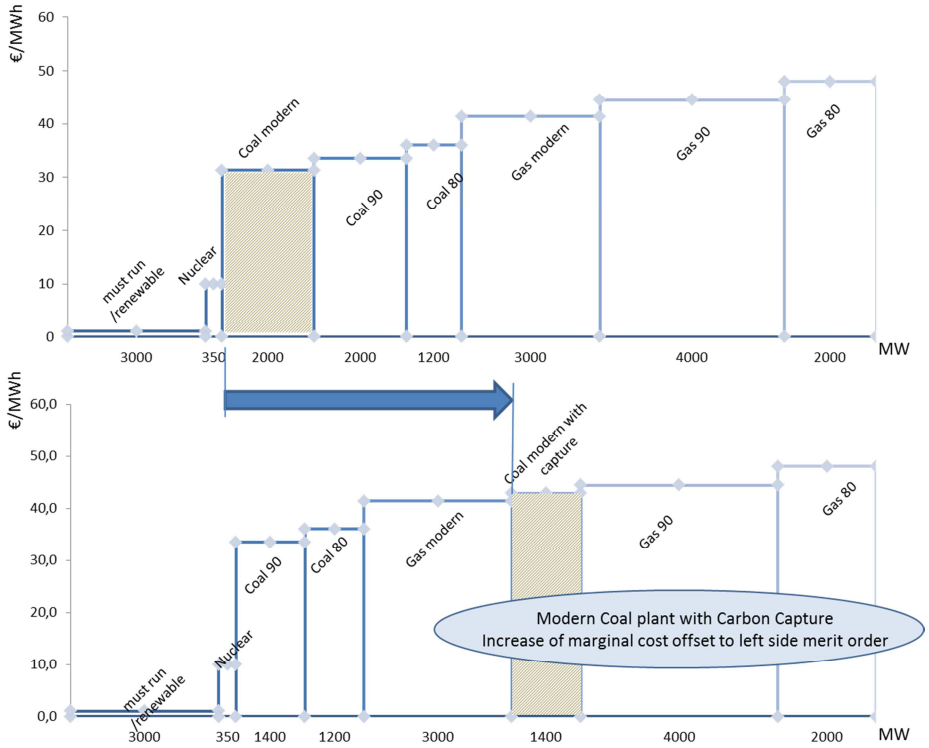

fig. 4 Implementation of carbon capture technology on the marginal cost of a modern Coal-fired power plant (merit order).

A shift towards an (obliged) implementation of CCS might be the future operational environment, in which coal-fired plants will need to operate. Plant dispatchers might have 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 carbon certificates. However, should CO_2 prices rise higher a trade-off will need to be made and an investment in further reduction of CO_2 emissions is required; i.e. capture technology.

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 [5]. The increase in renewable (i.e. wind/solar) and nuclear power generation typically have lower marginal generating costs than coal. On the other hand gas-fired plants have, presently, higher marginal generating costs but will have lower carbon costs. These, mix of more renewable and gas-fired power plants could then encroach on the base-load generation position of coal based power plants. In particular the competition for base-load generation will come from gas-fired power plants in the near future, see also

figure 4. The added benefit of gas-fired power plants in contrast to renewable is the provision of auxiliary services and can maintain system security. Furthermore, to achieve the challenges set forth by the European Union member states will have to make drastic changes to their energy portfolio; within the timeframe presented the fastest and straightforward option would be to increase the share of gas-fired power plants. This will surely decrease the viability of coal as a base-load operator.

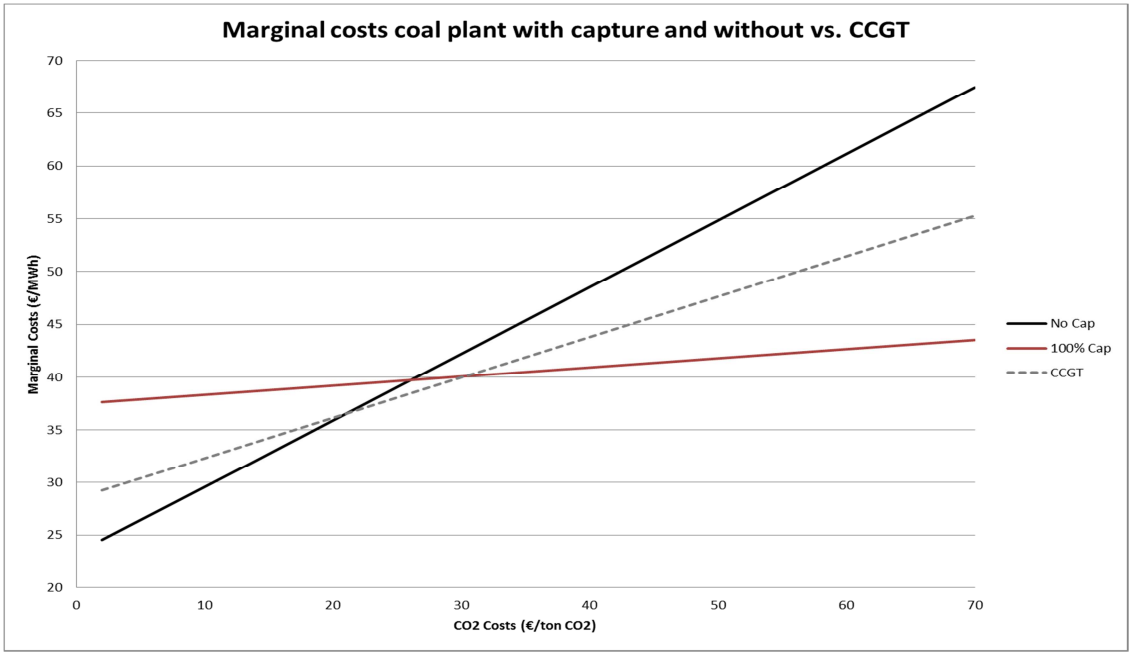

fig. 5 marginal Costs of a coal plant with and without capture vs. CCGT plant

In figure 5 the marginal costs for a Combine Cycle Gas Turbine (CCGT) is plotted against that of a coal-fired plant with and without capture. At lower CO_2 prices the coal-fired plant without capture will out naturally out-compete a coal plant with capture and also maintain a better merit order than a CCGT plant. When CO_2 prices increase to around €22 per ton CO_2 a CCGT plant will have lower marginal generating costs than a coal plant without capture; i.e. replacing coal on the merit order as a base-load power plant. The gross sum of coal plants are not equipped to handle variable loads and will, therefore, become superseded. However, should the coal plant invest in capture, it is able to reduce its marginal costs in relation to a coal plant without capture at higher CO_2 prices.

Around €32 per ton CO_2 coal plants with capture will become competitive with CCGT without capture. Should Carbon price rise even higher the coal plant with capture retakes its position on the merit order as a base load provider if no other changes to the energy portfolio occur. As such, increasing the relative size of the capture unit at a powerplant when carbon price forwards tends to increase is a logical move. See figure 6 for the marginal costs with different number or size of capture unit at the same power plant.

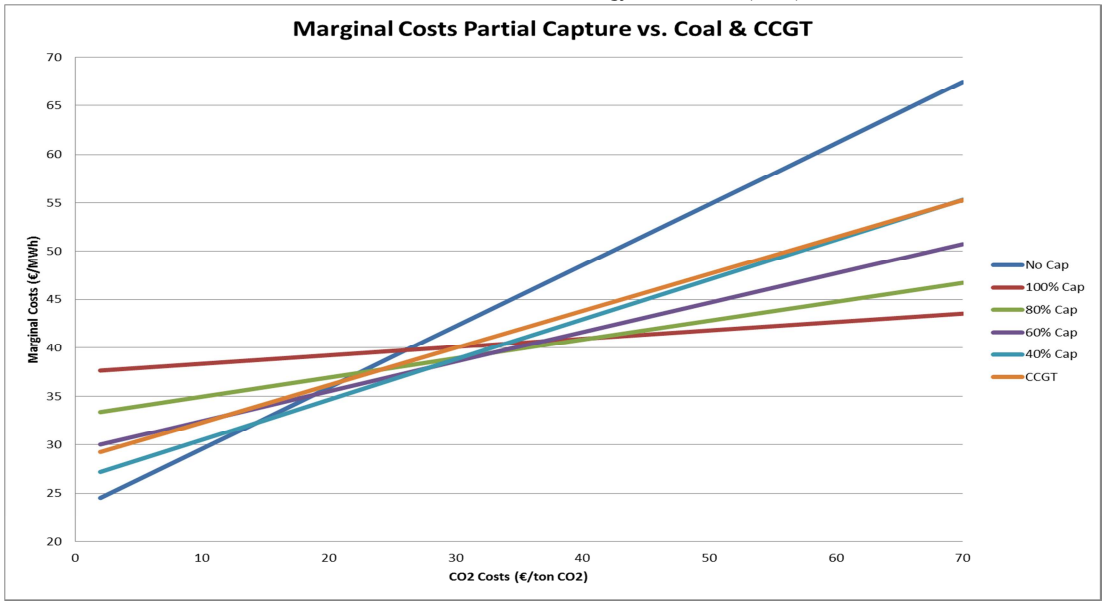

fig. 6 marginal costs different size capture units

2.4. Investment analyses

The NPV analyses is based on different (size) number of capture units and flexible operation of the Capture Unit, which allows to make a consistent comparison whereas the introduction of the various Market scenarios provides the possibility to study the sensitivity of the project and facilitates technology selection unambiguously. See figure 7.The different prices forward scenarios are based on typical NW-Europe market spreads. The base case current scenario reflects the average market prices at 2011 in NW-Europe. The renewable case consists of an increase of renewable capacity and the high gas low coal case assumes a very tight market for gas. The base case scenario is based on the average spreads over the last 5 years in NW-Europe. For all the different scenarios the carbon price is set at very moderate prices (ranging between 10 €/ton CO_2 up to 20 €/ton CO_2).

It is obvious that the size of the Carbon Capture unit heavily influence the economics of the power plant and at normal market condition with reasonable spreads a flexible operation of the Carbon Capture introduces an attractive option for power plant dispatcher. The FOMs creates a significant amount of NPV value improvement and therefore, it is justified to look in much more detail how the flexibility of a power plant can be improved integrated with a Carbon Capture unit.

Running a power plant with a 100% capture unit at base load will require significant amount financial support to close the gap. Starting with a smaller capture unit reduce the financial risk and might improve the business case of the coal-fired power plant without a CO_2 Capture Unit from a marginal cost point of view. The main reason for this is the increase of flexibility, by switching on/off the capture unit, an additional option value is created.

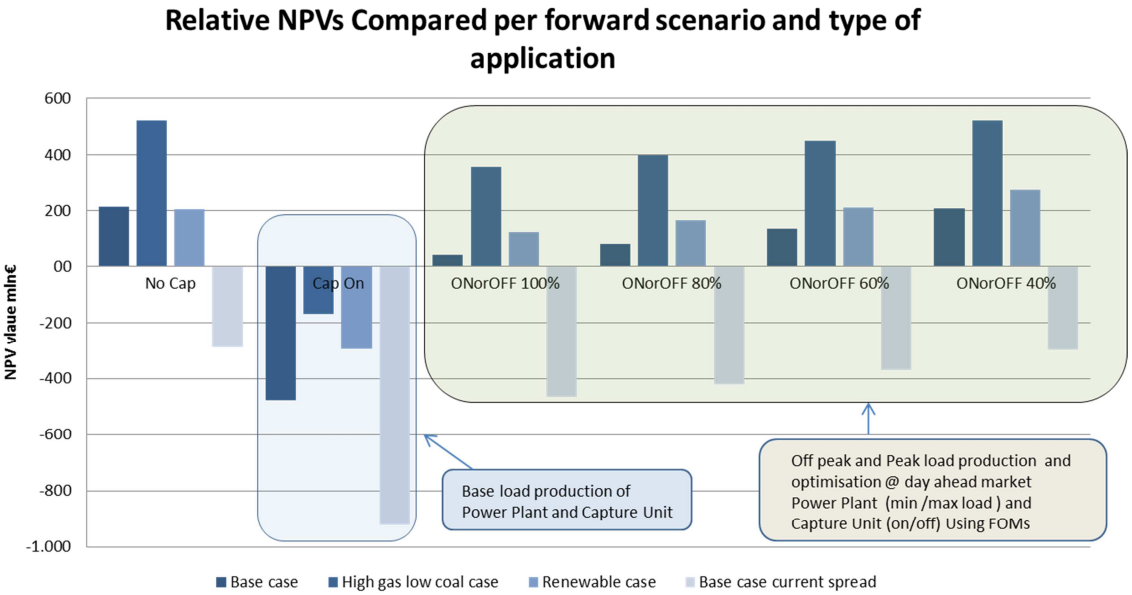

fig. 7 relative NPV analysis at different forward price scenarios and capture size.

3. Discussion

The focus is mainly on the capture unit but it is obvious that the entire chain must be considered to enable this flexible operating mechanism. As such liquefaction and intermediate storage of CO_2 might be required for flexible operation of the Capture plant.

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 is using to generate electricity from steam by burning coal. Assuming 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. FOMs could improve the flexibility of a coal-fired power station, but it might requires several adaptation in the capture unit and integration to facilitate on/off operation.

Most energy companies strive to maximize the value by optimizing the dispatch of power assets. The way companies optimizes vary from very straightforward priority tables or very manually in the form of sending emails to the operations room of the power plant with a list of set points which has to be gone through. Sending on hourly basis a list of set points is also very common in the Power industry. The manual interloping does not make the system predictable and can introduce mistakes and less optimal power plant exploitation. Conclusively there is a lack of a system which secures the most optimal dispatch of assets. Hence applying FOMs requires also a modern approach of dispatching.

It is very common to sell a majority of the power production of the respective coal-fired power plant in the forward market, while at the same time purchasing forward the required fuels (Coal) and CO_2 credits. This is so-called “hedging”. Hedging a power plant serves the following two main purposes:

1. Reduce market risk: First, with hedging the dependency on price levels of highly volatile spot markets decreases. In relation to this, hedging reduces potential liquidity issues on spot markets.
2. Profit optimization: Forward Spreads may vary over time. Dynamic trading strategies can increase value by selling more power against high spreads and selling less power (or buying it back) against low spreads.

The application of carbon capture FOMs enables additional flexibility for hedging and dynamic trading strategies. These additional features have not fully been addressed in the TNO valuation model and should be considered as an additional feature for the traders.

4. Conclusions & Recommendations

This article shows that it is important to properly reflect the flexibility of a power plant in the valuation. Based on the results of the techno-economic modeling, FOMs improve significantly the economic business case. Next to this FOMs present coal fuelled power plants with additional flexibility. This added flexibility could allow coal plants to provide auxiliary services to the grid and remain competitive in relation to cleaner gas-fired plants at lower CO_2 prices.

However, the fuel, CO_2 and electricity prices will decide whether or not a capture plant is built, although the decision to invest is always affected by the opportunity costs of making a commitment now, and thereby giving up the option of waiting for improved market condition. When the operational environment is favorable, an initial investment in a smaller capacity of capture (e.g. 40%), whilst employing the flexible operating mechanism is preferable under most conditions. In the model the 40% size capture plant has shown to be most robust in all scenarios developed. Should prices of CO_2 rise faster than predicted an add-on to the this capture plant can be build. The main benefit of the FOMs is that they create value at

lower CO_2 prices than a reference plant with capture. Furthermore, starting with a typical proven size capture unit and increasing the amount of capture units over a certain time window will at the end lead to a quicker and robust investment scheme. Finally, the combination of sizing and flexible dispatching Carbon Capture technology will reduce costs and, therefore, improve the economic feasibility of carbon capture at coal fuelled power plants.

The increase of operational flexibility with FOMs, creates a significant improvement of the NPV value and, therefore, it is justified to look in much more technical detail how to improve the operational flexibility of a coal-fired Power Plant with Carbon Capture.

Acknowledgements

The authors would like to thank the CATO-2 program, coordinators and sponsors for financing this research.

References

[1] Verbaan, M. “Flexible Operating Mechanisms Improving the Business Case for Pulverized Coal Power Plants with Post Combustion Capture” TNO (2011).

[2] Reference base-case from CESAR D2.3.1 work package (2010)

[3] Market data from several websites, Point Carbon, Platts, etc, (2011)

[4] Scenario model by Burdock Energy (2011)

[5] Chalmers, H., M. Lucquiaud, et al. (2009). "Flexible operation of coal fired power plants with post combustion capture of carbon dioxide." Journal of Environmental Engineering 135(6): 449-458.