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COAL OPTIONS

Evaluation of coal-based power generation in an uncertain context

Summary

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CONTENTS

FIGURES 2
TABLES 2
ABBREVIATIONS 3
SYMBOLS 3
SUMMARY 4
1 OBJECTIVES 4
  1.1 Global issue 4
  1.2 Goal 4
  1.3 Research strategy 5
    1.3.1 TERM 5
    1.3.2 CORE 5
2 RESULTS 6
  2.1 Gas-fired and coal-fired power plants performances 6
    2.1.1 Technical options 6
    2.1.2 Current power plants performances 6
    2.1.3 Potential for innovation 8
  2.2 Risk analysis 9
    2.2.1 Fuel prices and electricity prices uncertainty 9
    2.2.2 CO2 emissions mitigation uncertainty 9
  2.3 Plant valuation 9
  2.4 Investment decision model 9
3 CASE STUDIES : NGCC VERSUS IGCC 10
  3.1 Fuel prices evolution 10
  3.2 Economic Analysis 11
    3.2.1 NPV analysis 11
    3.2.2 Valuing flexibility 11
4 CONCLUSIONS AND PERSPECTIVES 14
  4.1 Fossil-fuels performances 14
  4.2 Real options methodology 14
  4.3 Fossil fuels and climate change 14
  4.4 Competitive and uncertain electricity market 14

FIGURES

Figure 2-1 : NGCC investment cost : effect of size (*GTW, 1996-2001*) 7
Figure 2-2 : Specific CO2, NOx, SO2 and dust emissions of STAG, IGCC, PFBC and USC 7
Figure 2-3 : Experience curve for STAG power plants (progress ratio observed is 93%). 8
Figure 3-1 : Gas prices evolution (μ = 0,0299 and σ = 0,1165) 10
Figure 3-2 : Influence of the capacity factor (μ = 0,0299, σ = 0,1165, i = 0,1) 11
Figure 3-3 : Discounted cash flow 12
Figure 3-4 : Evolution of the minimum gas price required at repowering year for IGCC conversion 12
Figure 3-5 : Flexibility value gives the optimal repowering year 13

TABLES

Table 3-1 : Data for the reference case 11

ABBREVIATIONS

STAG	STeam And Gas combined cycle
CCGT	Combined Cycle Gas Turbine
NGCC	Natural Gas Combined Cycle
IGCC	Integrated coal Gasification Combined Cycle
PC-USC	Pulverised-Coal fired plants with (Ultra) Supercritical steam Cycle
GBM	Geometric Brownian Motion

SYMBOLS

t, y	time, year
t_0	commissioning year of the plant
t_R	repowering year
n	lifetime, year
I	specific investment cost, EUR/kW
CP(t)	coal price at time t, EUR/GJ
P(t)	natural gas price at time t, EUR/GJ
P'(t)	natural gas price at time t, EUR/kWhe
$f_y[P(t)]$	probability density function of natural gas price at time t based on price given at time y
E_y [P(t)]	mean expected value of natural gas price at time t based on price given at time y, EUR/GJ
μ	mean expected growth, s^{-1}
σ	volatility, $s^{-1/2}$
α	trend, s^{-1}
I	discount rate
U_t	annual utilisation for year t, hours/year
FOM(t)	fixed O&M costs for year t, EUR/kW.year
VOM(t)	variable O&M costs for year t, EUR/kWh
EGC	electricity generating cost, EUR/kWh
NPV_t	net present value based on natural gas price information given at time t, EUR/kW
ROVt	real options value based on natural gas price information given at time t, EUR/kW
FV	flexibility value, EUR/kW
OC	option cost, EUR/kW

SUMMARY

1 OBJECTIVES

1.1 Global issue

Consequences of the new competitive European electricity market on power plant investment decisions.

Towards a better treatment of uncertainty.

Uncertainty has reached an unprecedented level in the European electricity market: impacts of the liberalisation on power companies and on electricity prices, evolution of long-run natural gas prices, evolution of the greenhouse gases reduction commitments, evolution of emissions standards (SO_2, NOx, dust,…), performances of newly emerging technologies.
It has been recognised in the last ten years by major lenders that investments in the energy sector in general, and in the electricity sector in particular should not be driven by the simple net present value criterion. The reason is the uncertainty that normally surrounds the energy field. Interestingly enough it has long been recognised in other energy areas, and in particular in energy consuming industries that investment choices are effectively not always dictated by this criterion. Future uncertainty is in those cases too often mentioned as the reason to depart from the pure application of net present value computation. While regulated companies like power companies have, in the past, been able to pass uncertainty to their customers, this will no longer be possible in the future.

Opportunities for emerging power plant technologies?

Serious mistakes on the assessment of the possibilities of technologies can be made if the methodology does not take into account their capability to adapt to uncertainty ("flexibility"). Therefore, flexibility need to be taken into account when assessing the economic potential of alternative technologies with respect to their main competitors.

Which impact on CO_2 emissions?

Extensive use of such new investment decision methods in the power industry will probably modify the generation capacity mix and thus have an impact on CO_2 emissions dedicated to electricity generation.
Moreover, instruments introduced by public authorities mainly modify the economic and technological parameters of the relevant technologies. Their effectiveness is thus also affected by the prevailing uncertainty. The same shortcomings will thus also be found in the evaluation of their effectiveness if one restricts oneself to standard techniques that do not account for the ability of technologies to adapt to uncertainty.

1.2 Goal

Analysis of competition between fossil fuel power plants by means of the theory of real options

Limitations of greenhouse gas emission from large-scale fossil fuel-based power plants are probably a key element of a strategy towards sustainable development. The power sector is currently driven by a dash for gas that, at least partially, contributes to the desired result when substituting for less efficient coal power plants. Major characteristics of the natural gas-fired combined cycle plant are high efficiency, low investment costs, low environmental impact, short installation time and good operating flexibility. Many expect that for reasons of resource availability and/or production and transportation cost of the natural gas, this evolution will be limited in time.
In this case, whatever attitude towards nuclear energy and renewables, new investments in coal power plants will probably be considered. In comparison to other fuels, coal is characterised by important reserves and lower prices but also by much higher emissions of pollutants. Newly emerging coal-based technologies with more efficient conversion of coal and improved environmental performances appear then as a main option to limit greenhouse gas emission with respect to

conventional coal power plants: they will thus have to be considered in any strategy of the power sector to contribute to sustainable development.
In an uncertain context, are these new, less polluting but more expensive innovative coal power plants competitive in comparison to gas-fired STAG units and more conventional coal power plants? What are the capabilities to adapt to uncertainty ("flexibility") of these power plants? What are their economic values?
The theory of real options applies to power plant valuation and optimal investment decision modelling allows a more adequate treatment of uncertainty than methods based on a net present value computed over a set of scenarios. The idea of the theory is that a less flexible equipment is at a disadvantage that is not included in the standard net present value calculation. Then, this theory gives an economic value to power plants flexibility's such as fuel switching, repowering opportunities, capability to adapt to the standards of emission and operational flexibility.
This approach directly draws on the theory of financial options initiated in the celebrated work of Black-Scholes (1973). It culminated in the book of *Pindyck and Dixit (1994).* The idea was well publicised by the World Bank which first pointed out the drawbacks of using net present value calculation for assessing the relative competitiveness of equipment that have quite different characteristics of flexibility. The relevance of the theory of both financial options and real options is illustrated by the importance taken by this subject in several energy companies in the world. It is noticeable that this work has also found its way into issue of sustainable development.

1.3 Research strategy

Development of a tool taking into account uncertain facfors for the analysis of competition between coal-fired and gas-fired power plants in the mid- and long run.

1.3.1 TERM

Technological characteristics (technical, environmental, economic and flexibility) and potential for innovation (in the mid- and long-run) of coal and gas-based power plants

Specific objectives are:

1. Identification and characterisation of main coal-based and gas-based technologies
2. Performances of current power plants
3. Scenarios of evolution of these performances in future
4. Flexibility characteristics of these power plants
5. Scenarios of evolution of these performances in future
6. Case studies by integration of the data generated by TERM in the model developed by CORE

These objectives have been achieved by data collection from scientific publications, trade journals and manufacturer communications and by the development of physico-chemical / thermodynamic / techno-economic power plant models.

1.3.2 CORE

Application of the real options theory

Specific objectives are:

1. Risk factors modelling : stochastic processes selection and calibration for fuel prices, electricity prices and CO2 emission permits
2. Development of a power plant valuation model
3. Development of power plant investment decision model

2 RESULTS

Main results provided by this project are:

1. A method for techno-economic optimisation of electric power plants that make it possible to estimate the potential of innovation. This method will be transposable to other types of thermal power plants (combined heat and power systems, biomass gasification systems,…). Results consist of database and models.
2. Standard performance curves and scenarios for each technological options considered.
3. Calibration of stochastic processes (fuel prices, electricity prices and emission permits).
4. A methodology for power plants valuation and investment decision in a competitive organisation of the industry, considering a financial value for power plants flexibility's.

Unfortunately, due to a lack of human resources it has not been possible to integrate these flexibility options in the model. Only limited case studies based on a simplified approach have been performed simulating competition between gas-fired and coal-fired power plants or between state-of-the-art power plants and innovative concepts.

2.1 Gas-fired and coal-fired power plants performances

Power plants considered are limited to gas-fired STAG units (STeam And Gas turbines combined cycles) and coal-fired IGCC (Integrated Gasification Combined Cycle) and PC-SC units (Puliverised Coal SuperCritical steam cycle).

2.1.1 Technical options

For each technology considered (STAG, PC-USC, IGCC), several technical options have been selected and standardised according to the following classification:

Physico-chemical data
- fuel conditioning and feeding
- nature of the oxidant or the gasifying agent
- combustion / gasification conditions

Thermodynamic data
- gas turbine cycle conditions (pressure and temperature)
- steam cycle conditions (pressure and temperature)

Environmental data
- fuel gas treatment (IGCC)
- flue gas treatment (dust, NOx, SO2)
- solid and liquid residues

2.1.2 Current power plants performances

We have only considered commercial plants or demonstration plants at commercial scale (e.g. Buggenum IGCC power plants in The Netherlands). For each identified power plant, the following data have been collected and standardised (fuel composition, air and cold-end conditions,…) :

Techno-economic performances

1. Installed capacity
2. Full load and part load efficiency
3. Investment cost
4. O&M costs

On this basis, two types of **standard curves** have been achieved:
1. Effect of size for efficiency, investment cost, O&M costs (see Figure 2-1)
2. Part load efficiency

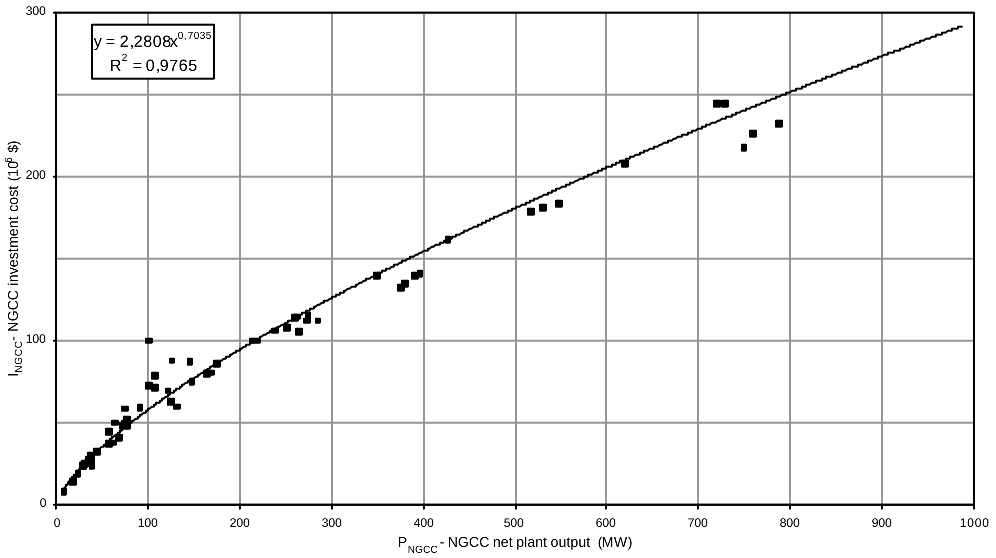

Figure 2-1 : NGCC investment cost : effect of size (*GTW, 1996-2001*)

Environmental performances

We have only considered emission related to power plant operation. Emissions from fuel extraction, transport, power plant building and dismantling are therefore not considered, as it's the case with the LCA approach.

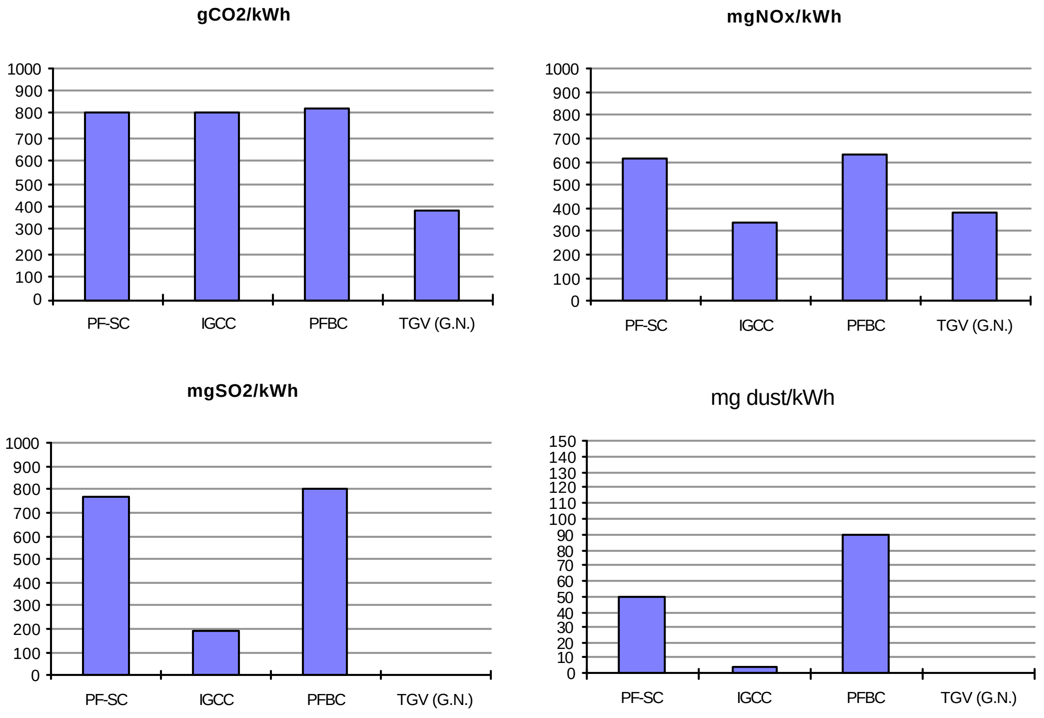

Figure 2-2 : Specific CO2, NOx, SO2 and dust emissions of STAG, IGCC, PFBC and USC

In this study, CO2 capture technologies in flue and fuel gases are not considered. Then, CO2 emissions are simply derived from power plant efficiency and fuel composition. In addition of these parameters, combustion/gasification conditions and flue gas treatment are used to assess NOx, SO2 and dust specific emissions. On this basis, standard curves have been obtained (effect of size for specific emission and specific emission at part load).

2.1.3 Potential for innovation

Evolution of power plants performances has been obtained by the following way:

1. Evolution of major technological parameters:

   The selected parameters are only those related to the thermodynamic cycle (maximal firing temperature of the gas turbine cycle and steam pressures and temperatures of the steam cycle).

2. Performance calculation by means of these technological parameters:

   Efficiency and specific emissions are obtained from physico-chemical and thermodynamics models of the various power plants considered. Some of the thermodynamic parameters are optimised according to a techno-economic criteria (e.g. steam pressures of the steam cycle in a STAG power plant).
   Concerning the investment costs, correlations from cost engineering databases and thermoeconomics developments are used to express the cost in function of thermodynamics parameters, material used and design of the components.

3. Combining step 1 and 2 gives us various scenarios describing the time-evolution of the performance (efficiency, specific emissions, investment costs) for gas-fired and coal-fired power plants.

4. Above-mentioned thermodynamic parameters are not the only driving force for improvement of power plants performances. Scenarios also include potential technological jumps identified in the frame of this project (hot gas filtration for IGCC, sequential combustion for gas turbine,…)

5. These scenarios are compared and completed by those obtained with the *experience curve* methodology *(Wene, 2000)*. In this case, a power function between price / cost or efficiency and experience over time, i.e. cumulative production of units, installed capacity, is derived from historical data. The time-evolution of power plants performance is then obtained from market development scenario (e.g. period for doubling the cumulative production) .

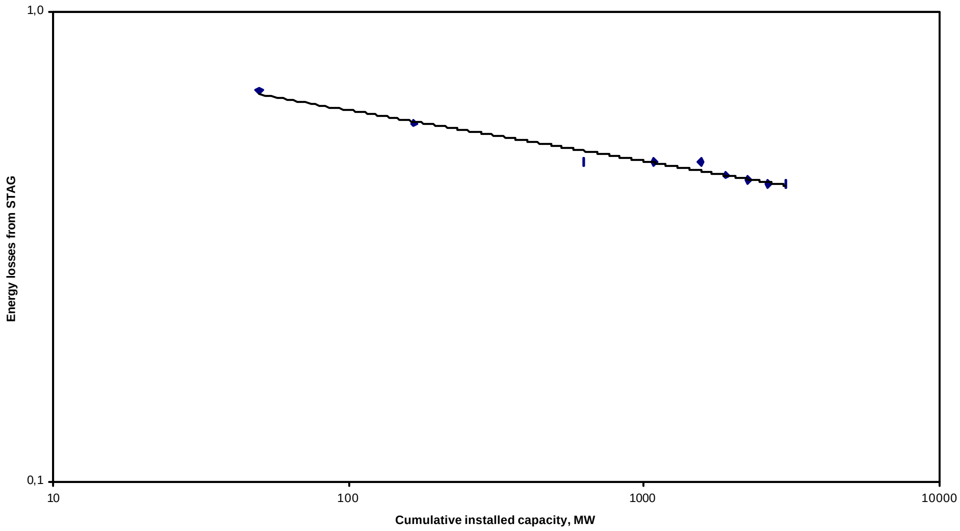

Figure 2-3 : Experience curve for STAG power plants (progress ratio observed is 93%).

These scenarios are only valid for an installed capacity range. They can be adapted by means of the standard scale laws in the case of other capacity range. These scenarios are dedicated to be used by the decision model developed by the CORE team.

2.2 Risk analysis

Only fuel prices, electricity prices and emission permits have been analysed. For these risk factors, suitable stochastic models have been selected and calibrated in order to predict efficiently the behaviour of main risks factors.

2.2.1 Fuel prices and electricity prices uncertainty

The theory of real options was relatively poorly endowed in computational terms at the time the project started. This quickly showed up in the work as the first year of the projects revealed important difficulties. Energy prices do not follow the standard diffusion processes found in finance and extensively used in the work done at the time in real options.

The formalism of affine jump diffusion processes may present some mathematical difficulties, but it allows one to represent many of the idiosyncrasies of electricity prices. Specifically affine jump diffusion processes are quite suitable for modelling mean reversion (which is a characteristic of all energy prices) and jumps (which are particularly important in electricity but also arise in natural gas).

2.2.2 CO2 emissions mitigation uncertainty

Discussion with MIT specialist in emission trading Dr D Ellerman led us to model this uncertainty though prices of emission permits. Even though it is not certain that this policy instrument will prevail, the slow progress of the Kyoto protocol leads one to conjecture that some more structured arrangement will need to be developed and that emission permits on a global scale will emerge. Sticking to the overall methodology of real options, the problem is then to model the stochastic process that describes the evolution of the price of these permits. The idea was to fit a diffusion process with jumps at well specific periods of time. This suggestion emerged from discussion with Professor Emeritus A. Manne from Stanford University. Prof. Manne is directing the Energy Modelling Forum project on global working. The results of models run in the context of this project provide the necessary information to model this price process.

2.3 Plant valuation

The model developed gives the value of an investment realised at a certain date. The value of a plant is modelled as a strip of European options on spark spread between electricity and fuel prices (two stochastic factors model). In more usual terms, this equal to the integral, over the life of the plant, of an option on the difference between the price of electricity and the cost of fuel. In addition to the initial option to choose the type of power plant, one will be able to consider the option to stop or start-up the production of electricity depending on the price of electricity in market.

Progress on Fourier Transform analysis and Monte Carlo simulation, based on the affine jump formalism, have been written for this plant valuation process.

2.4 Investment decision model

To model the investment decision in power plants through a realistic and computable real option model, we retained the formalism of American options on differences (spread) between electricity and fuel (gas or coal) prices to do so. The payoff of this option, when exercised, is the value of the plant computed by the plant valuation model. American options on spreads are a novel problem. A program based on complementary formulation of this American option has been written. Consequently, in addition to above-mentioned options, one will be able to consider the option to delay the investment and consequently to find the optimal date for investment.

3 CASE STUDIES : NGCC VERSUS IGCC

A simple approach based on the real options theory has been proposed to determine the optimal investment decision for a new power plant in an uncertain context. Two projects are considered : a natural gas-fired CCGT power plant (NGCC) and a coal-fired IGCC power plant. In addition, the flexibility value of a phased construction for IGCC power plant is analysed (financial value for the repowering option to convert a NGCC unit into an IGCC unit). The uncertainty considered is the natural gas price evolution. A Geometric Brownian Motion (GBM) stochastic process has been used and calibrated by means of various historical data and scenarios.

3.1 Fuel prices evolution

In most scenarios, due to large reserve of coal and its wide distribution in the world, coal price is supposed to be stable over a long-term period. For that reason and to simplify real options computation, we consider a constant coal price over the entire period. Consequently, only the natural gas price is considered as a stochastic variable. Several calibration of the mean expected growth rate μ and the annual volatility σ of the natural gas price have been performed. A first approach was based on historical values for the Belgian borderprice "all gases" from 1982 to 2000 and a second approach was based on 15 fuel prices scenarios for the period 2000-2010 or 2000-2030.

Figure 3-1 illustrates the evolution of the probability density function $f_{t0}[P(t)]$ obtained for $\mu = 0{,}0299$, $\sigma = 0{,}1165$, corresponding to a positive value for the trend $\alpha = 0{,}0231$, and $P(t_0) = 4$ EUR//GJ.

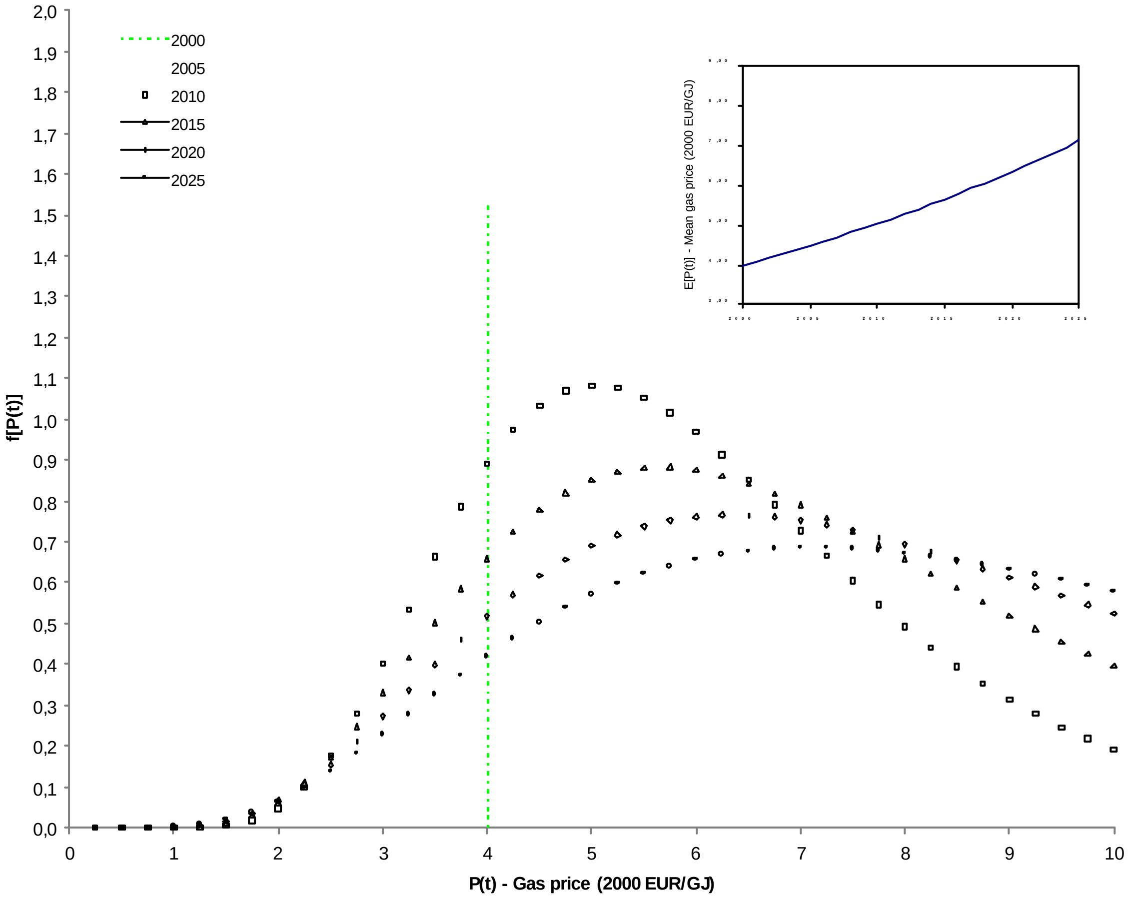

Figure 3-1 : Gas prices evolution ($\mu = 0{,}0299$ and $\sigma = 0{,}1165$)

3.2 Economic Analysis

3.2.1 NPV analysis

Calculations are based on the discounted cash flow techniques. Discounted electricity generating costs are calculated according to the UNIPEDE method.

A first step in the analysis is the comparaison of the Net Present Value (NPV) of an IGCC project versus a NGCC project where a mean natural gas price evolution is derived from a stochastic process. Table 3-1 summarises inputs used for the reference case calculation.

	NGCC	IGCC	
Investment	400	1200	EUR/kW
Efficiency	55	45	% LHV
Fuel price	4	1,5	EUR/GJ

Table 3-1 : Data for the reference case

Influence of the annual utilisation U on the discounted electricity generating cost is given by Figure 3-2 with μ = 0,0299, σ = 0,1165 and a 10 % discount rate. In this case, the trend α has a positive value. It shows that IGCC is less expensive for annual utilisation above 4500 hours a year (which is usual for such plants).

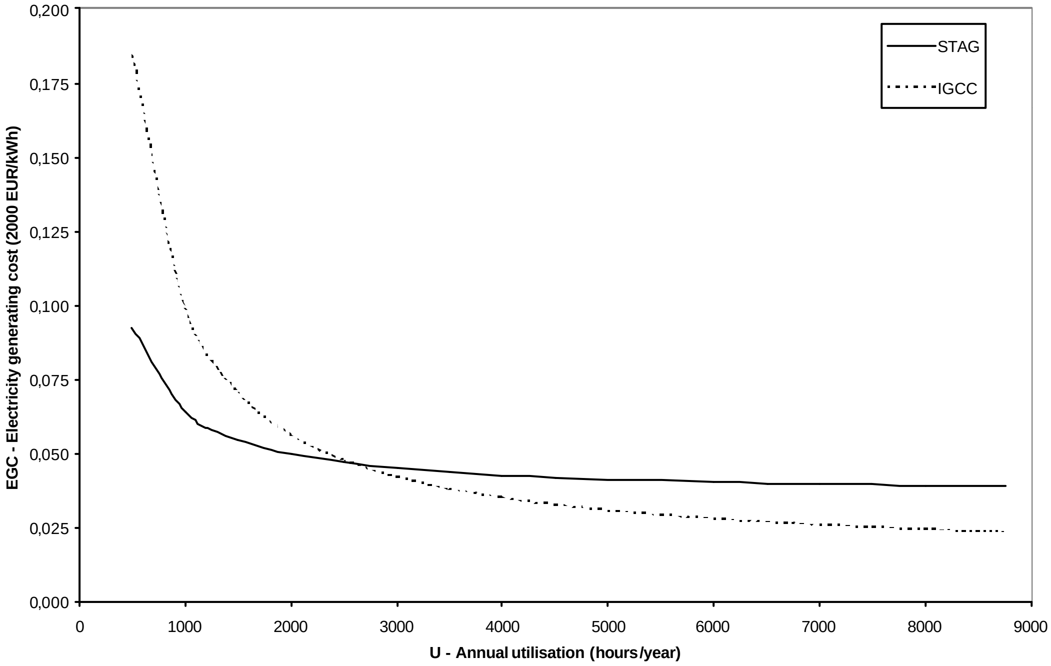

Figure 3-2 : Influence of the capacity factor (μ = 0,0299, σ = 0,1165, i = 0,1)

3.2.2 Valuing flexibility

We consider now the possibility of a phased construction. Three new parameters could be considered, (1) the additional cost for STAG unit convertible into a IGCC power plant (fuel gas burner lines, space requirements, supply logistics,...) corresponding in financial term to the option cost (OC), (2) the net efficiency drop (ED) of such STAG units in comparaison with best available STAG units and finally (3) the repowering year. In this study, the potential increase of the power plant capacity when repowered to an IGCC has not been considered. Figure 3-3 shows the discounted cash-flow during power plant lifetime with a repowering occuring in 2010. No additional costs and no efficiency drop have been considered for this calculation. GBM considered parameters are μ = 0,0029 and σ = 0,2279 with discount rate of 5%.

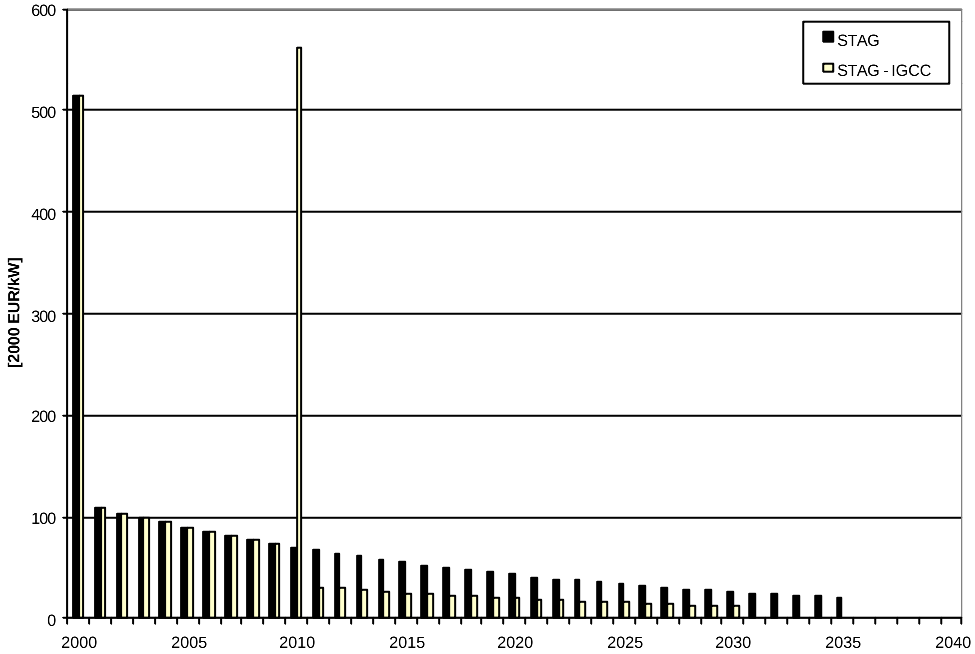

Figure 3-3 : Discounted cash flow

In the conventional analysis, the decision criteria is the difference between the expected net present value (NPV) of two projects, (1) STAG investment, (2) STAG investment and IGCC conversion at a fixed repowering year. The second project has to be selected if its NPV is better than the NPV of the STAG investment.

In the conventional analysis, the natural gas price evolution used for calculation is based on the price value at the reference year. In the real options analysis, the conversion to an IGCC power plant will only be done if the NPV of the conversion evaluated at the repowering year is positive (fuel price evolution are based on fuel price level at repowering year). The thresold of the observed natural gas price at the repowering year from which the NPV_r becomes positive and repowering has to be dediced in shown in the following figure for the reference case.

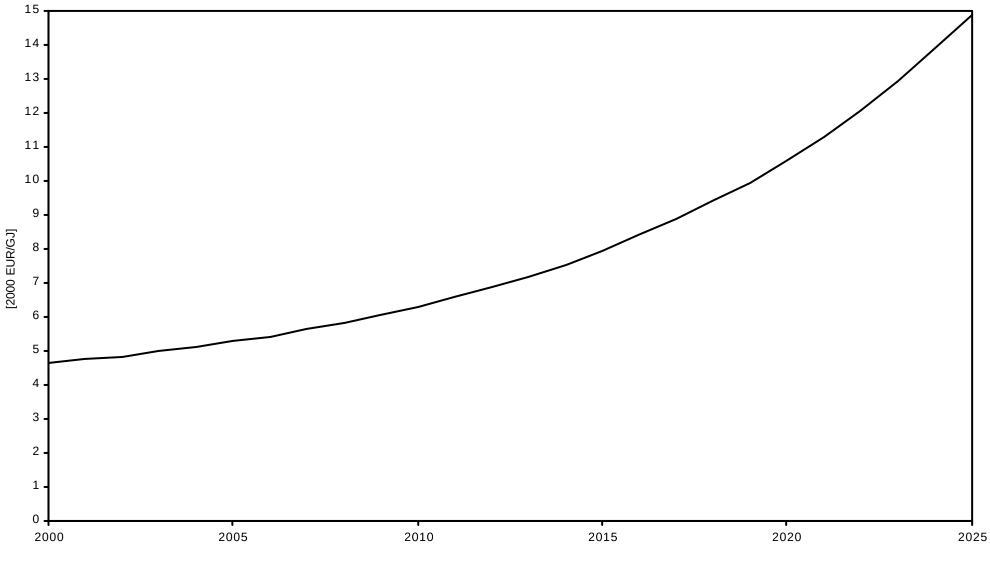

Figure 3-4 : Evolution of the minimum gas price required at repowering year for IGCC conversion

Figure 3-5 shows the evolution of the difference between the real options value (ROV) and the conventional NPV in function of the repowering year. This difference is corresponding to the so-called flexibility value (FV) for i=10%, OC = 0%, ED = 0%). In this case, the optimal repowering year for repowering is 2006.

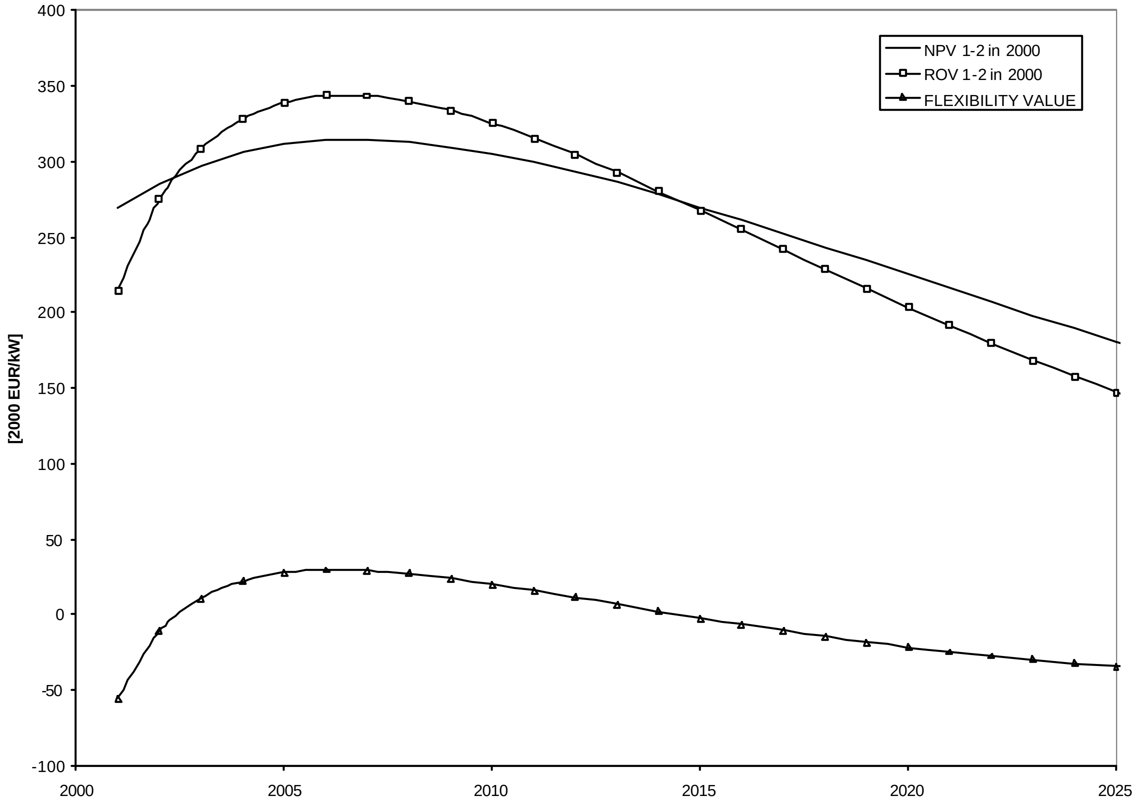

Figure 3-5 : Flexibility value gives the optimal repowering year

4 CONCLUSIONS AND PERSPECTIVES

4.1 Fossil-fuels performances

Methods for the optimisation of techno-economic parameters of power plants have been implemented on conventional thermodynamic models.

Results consist of databases, thermodynamic and techno-economic models, standard performance curves and scenarios for each technological options considered for gas and coal-fired power plants.

The methodology of "learning curves" is well suited for combined cycle technology and in particular to predict the evolution of power plants performance such as investment cost or efficiency.

In future projects, these methods will be applied to other types of thermal power plants (combined heat and power systems, biomass gasification systems,…).

4.2 Real options methodology

A simple method based on a stochastic modelling of the natural gas price evolution is now available. Calibration of the stochastic process for natural gas price provides a convenient way to compare on a same basis historical data and scenarios for fuel prices evolution. Nevertheless, the electricity generating cost derived from this method is still very sensitive to fuel price parameters and other economic parameters such as the discount rate.

A more innovative contribution of the real options theory is to give a monetary value of a phased construction flexibility as demonstrated in the case of a repowering option of a STAG unit into a IGGC unit. In addition, the optimal repowering year can be calculated.

Nevertheless, further developments have still to be performed such as the use of more suitable stochastic processes for coal and gas prices evolution, a better integration of the technology evolution by the use of experience curves. Another major improvements of the method in this context of competition is to consider a stochastic process for the capacity factor or the use of the maximisation of the spark spread between electricity and gas as decision criteria instead of minimisation of the electricity generation cost. These improvements require more sophisticated calculation methods.

4.3 Fossil fuels and climate change

For period 1990-2010, progress in gas-fired and coal-fired power plants have allowed a specific CO_2 emission reduction (g/kWh) of more than 15…20 %. In comparison to Kyoto targets, it seems to be significant but with respect to the climate change problem it seems to be insufficient. Consequently, new fossil fuel power plants require necessarily integration of CO_2 separation systems. In this context, IGCC systems seems to be a very promising technology even if a large amount of R&D is still required.

4.4 Competitive and uncertain electricity market

Basic case studies based on conventional analysis or real options analysis show that for period 2000-2010 more efficient coal power plant complying with more stringent emission standards will be competitive with gas-fired combined cycle. This is mainly due to the positive trend for the gas price evolution predicted in most scenario.