

## GASIFICATION FOR COMBINED PRODUCTION OF ELECTRIC POWER AND CHEMICALS

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### Abstract

The Chemical Industry is confronted with a difficult challenge: how to deal with natural gas supply security and price volatility.

Solid gasification integrated with a combined cycle (IGCC) is a promising answer to these needs: it is a commercially proven technology available for the combined production of electric power and chemicals from coal and petcoke. IGCC is also the technology that facilitates the retrofit of CO<sub>2</sub> capture with a moderate capital pre-investment in the base configuration.

Two case studies are developed in the paper in order to depict a range of possible technical alternatives that can fit the specific requirements of each company:

- Co-production of ammonia/urea and electric power from petcoke gasification.
- Co-production of methanol and electric power from coal gasification. Methanol is considered either a final product or an intermediate for production, through a Methanol to Olefins step (MTO), of the required chemical products.

The alternatives, based on oxygen blown entrained bed gasification, are CO<sub>2</sub> capture-ready plants, sized to produce different amounts of electric energy and chemicals. Overall performances and investment costs are evaluated and discussed through a sensitivity analysis on cost of electricity (COE) and cost of chemicals (COC). Loss of performances and additional costs due to the CO<sub>2</sub> capture retrofit are also evaluated.

## Basis of design

The study is based on commercially available technologies and evaluates costs and plant performance of plants that can be presently engineered and built.

Two alternative IGCC plant configurations for the combined production of chemicals and power are investigated:

- Bituminous coal-based IGCC, designed to produce 5,000 t/d of methanol and to satisfy the appetite of one 250 MWe F class gas turbine (IGCC-MeOH).
- Petcoke-based IGCC designed to produce 3,400 t/d of urea and to satisfy the appetite of one 120 MWe E class gas turbine (IGCC-Urea). The gas turbine frame is selected in order to produce electric power as required by a modern refinery, with an overall petcoke consumption (derived from urea plus electric power production) meeting the delayed coker capacity (approx. 100,000 BPSD).

Plants are designed by considering a moderate capital pre-investment to facilitate the subsequent retrofit to allow CO<sub>2</sub> capture. Both cases separate the CO<sub>2</sub> from the synthesis gas in the base configuration, so the CO<sub>2</sub> capture retrofit mainly consists of the installation of the CO<sub>2</sub> drying and compression avoiding a prolonged plant shutdown to complete the conversion. These two retrofit alternatives are also investigated in the study (IGCC-MeOH with CCS and IGCC-Urea with CCS).

The IGCC plants are designed to process, in an environmental acceptable manner, bituminous coal and petcoke. Main fuel characteristics are:

- Bituminous Coal (BC): LHV equal to 25,870 kJ/kg and a sulfur content of 1.1% wt (dry, ash free).
- Petcoke (PC): LHV equal to 32,450 kJ/kg and a sulfur content of 6.7% wt (dry, ash free).

The location for the cost estimate is a generic European coastal site. The reference ambient conditions for performance evaluation are 15°C, ambient relative humidity of 60% and an average seawater temperature of 15°C.

The overall gaseous emissions from the IGCC complex, dry flue gas with 15% volume oxygen (O<sub>2</sub>), shall not exceed the following limits:

- NO<sub>x</sub> (as NO<sub>2</sub>) ≤ 50 mg/Nm<sup>3</sup>
- SO<sub>x</sub> (as SO<sub>2</sub>) ≤ 10 mg/Nm<sup>3</sup>

These limits are significantly lower than those defined by the applicable European directive and are set at these levels in order to minimize the emissions, without penalizing significantly the plant efficiency and investment cost.

Depending on the alternative, the plants produce the following main products and by-products:

- Electrical Power: Power is generated from the complex and transmitted to an HV substation for connection to the national grid.
- Methanol: Liquid Methanol at 99.85% wt purity is produced in the IGCC-MeOH alternative.
- Urea: Prilled or formulated Urea at 99.8% wt purity is produced in the IGCC-Urea alternative.

- Carbon Dioxide: For sensitivity cases with CO<sub>2</sub> capture, the CO<sub>2</sub> characteristics at the plant B.L. are: Pressure: 150 barg, Temperature: 30 °C, Moisture: < 0.1 ppmv.
- Sulfur: Sulfur is a by-product of the IGCC plant with the following characteristics: Liquid, Purity: 99.9 wt.%, H<sub>2</sub>S content: 10 ppmwt (max).
- Solid by-products: Slag and filter cake are produced by the gasification plant.

### Description of IGCC complex

The following description makes reference to Figure 1 and Figure 2, showing the IGCC block flow diagram and the main process streams of the two study alternatives (IGCC-MeOH and IGCC-Urea).

The main process blocks of the complex, common to the two alternatives, are the following:

- Feedstock storage and preparation;
- Air separation (cryogenic technology);
- Gasification, including black water/grey water treatment;
- Syngas treatment and conditioning;
- Acid gas removal (AGR);
- Combined cycle power generation.

These basic blocks are supported by other ancillary units, such as sulfur recovery, tail gas treatment, and a number of utility and offsite units, such as cooling water, flare, plant/instrument air, machinery cooling water, demineralized water and auxiliary fuels.

Each process unit of the complex may be a single train for the total capacity or split into two or more parallel trains, depending on the maximum capacity of the equipment involved or on the necessity to ensure, through the use of multiple parallel trains, a superior degree of reliability.

The key and first process step is the entrained flow gasification, which is suitable both for solid and liquid feed. In this type of gasifier the feed flows co-currently with the gasification agents (O<sub>2</sub> and steam). Residence time is very short, between 0.5 and 5 seconds; the temperature inside the gasifier is uniform and very high, from 1,300°C to over 1,500°C, well above the ash fusion temperature.

Recovery of gasifier sensible heat is made through a water quench inside the gasifier. The quench system allows efficient removal of solids from the raw gas, before entering the downstream facilities. In addition, water quench is beneficial for the downstream carbon monoxide (CO) shift reaction, which increases the H<sub>2</sub>/CO ratio. In fact CO shift requires large amounts of water which are directly present in syngas at the quench outlet.

Syngas main components are H<sub>2</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>O, as well as H<sub>2</sub>S and COS that need to be removed, and inerts. Downstream of the gasification, the shift reaction occurs on a catalyst suitable for processing H<sub>2</sub>S containing syngas (sour shift) to convert CO and water to H<sub>2</sub> and CO<sub>2</sub>. The shift catalyst promotes also the COS hydrolysis with its conversion to H<sub>2</sub>S and CO<sub>2</sub>. Raw syngas after cooling with heat recovery through a steam generator and water heating, is then treated in the AGR unit with a physical solvent that removes the acid gases (H<sub>2</sub>S, less

than 1 ppm, and CO<sub>2</sub>). The resulting syngas is free of any contaminant and prepared to produce both chemicals and electric energy.

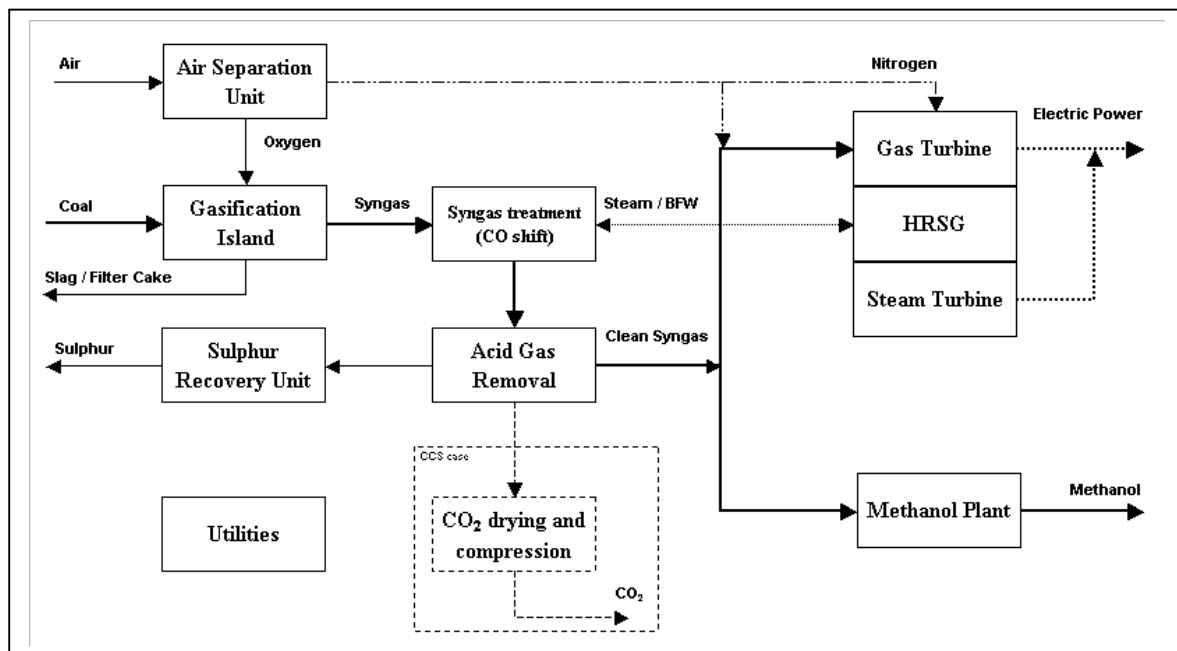
For the alternative with retrofitted CO<sub>2</sub> capture, after removal in the AGR unit, CO<sub>2</sub> is dried/compressed to 150 barg in order to be delivered to geological storage reservoirs. The cost of CO<sub>2</sub> storage depends on local factors, such as storage distance, pipeline diameter and type of reservoir. At some locations this cost is more than offset by revenues deriving from enhanced oil recovery, or embedded coal methane recovery, but at other locations transport and storage result in net additional costs. For these reasons specific storage costs have not been considered in the economical evaluations of this study. However an additional average cost for transport and storage equal to 10 €/t of CO<sub>2</sub> has been assumed to discuss the alternatives with CCS.

In the sulfur recovery unit, the H<sub>2</sub>S rich stream coming from the AGR regenerator is burned with oxygen in a muffle furnace, followed by two reactors in series where the Claus reaction takes place to produce liquid sulfur.

The oxygen required for both the gasification reaction and the Claus reaction is produced in the air separation unit (ASU), where air is fractionated by cryogenic distillation. The ASU also supplies N<sub>2</sub> to the gas turbine for NO<sub>x</sub> control and power augmentation.

### Electric power and methanol co-production plant (IGCC-MeOH)

The target of this alternative is to produce 5000 t/d and to satisfy the appetite of a nominal 250 MWe F-class gas turbine.



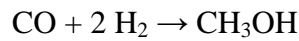
**Fig. 1** – IGCC Block flow diagram for Methanol and Electric Power Co-Production

Downstream of the shift reactor and the heat recovery, shifted syngas is cleaned in the AGR. The composition of the clean syngas at the AGR outlet shall meet the following specification, in order to be suitable for the methanol production:

$$(H_2 - CO_2) / (CO + CO_2) = 2.0$$

This specification is met with an average CO shift conversion of approx. 53% and a CO<sub>2</sub> capture rate equal to approx. 80%. The captured CO<sub>2</sub> is vented to atmosphere in the base configuration (IGCC-MeOH) or sent to geological storage (IGCC-MeOH with CCS). At the AGR outlet, a portion of the syngas goes to the methanol plant and the remaining part flows to the GT combustors.

In the methanol plant syngas is compressed in order to enter the methanol synthesis reaction. The main reaction involved in this catalytic process is:



Due to the limitation imposed by chemical equilibrium, the conversion achieved in the reactor is only partial. For this reason it is necessary to recycle the non-converted reactants. The liquid mixture of methanol and water is finally distilled in different columns to achieve the desired methanol purity.

### Electric power and urea co-production plant (IGCC-Urea)

The configuration of the gasification section is the same as the previous case, but the feedstock is petcoke. The gasifier produces enough syngas to feed a 120 MWe E-class gas turbine and the amount of hydrogen necessary for a 3,400 t/d urea plant.

The syngas exiting the gasification island is almost totally shifted in two shift reactors in series in order to maximize the hydrogen production. Downstream of the heat recovery, the syngas is cleaned by H<sub>2</sub>S and CO<sub>2</sub> in the AGR unit (approx. 90% CO<sub>2</sub> removal rate). At the outlet of the AGR part of the hydrogen rich fuel is sent directly to the gas turbine, while the remainder flows to the hydrogen purification achieved through a pressure swing adsorption (PSA). Hydrogen from the PSA has a purity of 99.8% vol. The PSA offgas is fed to the HRSG post-firing system.

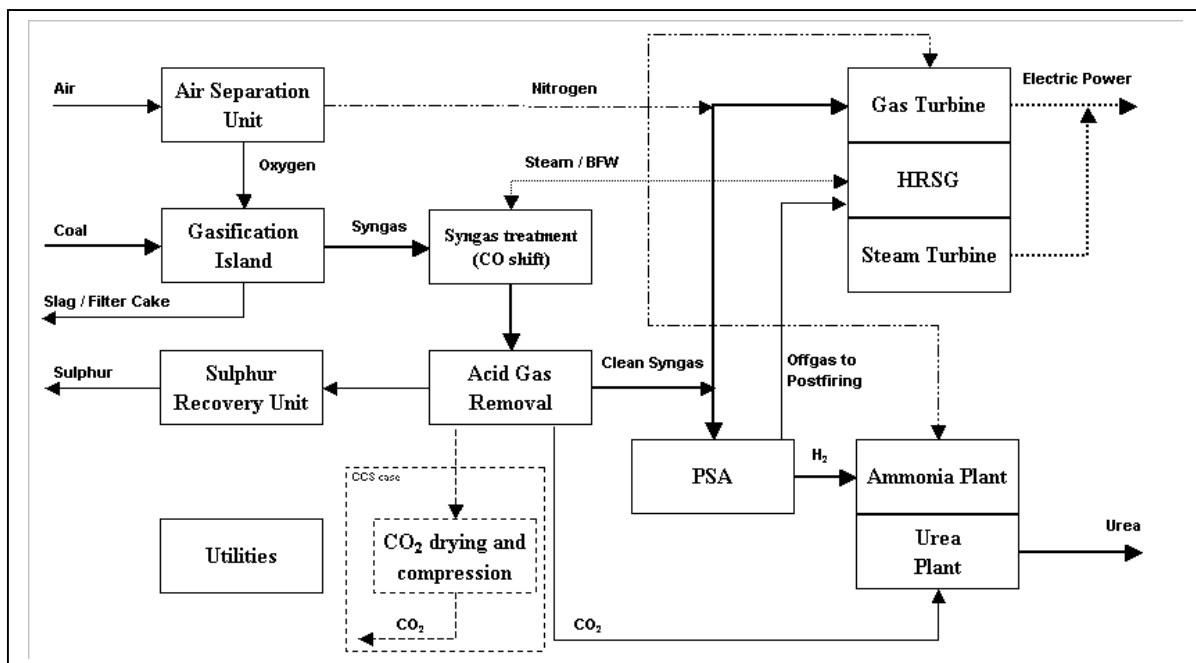
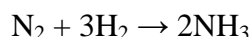


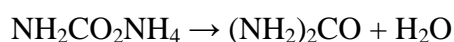
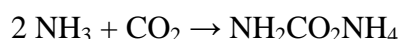
Fig. 2 – IGCC Block flow diagram for Urea and Electric Power Co-Production.

Almost pure hydrogen from PSA is blended with nitrogen, compressed, heated and partially converted to ammonia according to the following catalytic reaction:



The ammonia produced is cooled and separated from impurities. The non-converted portion is recompressed, recovered from ammonia, mixed with make up synthesis gas and sent back to the ammonia converter.

Pure CO<sub>2</sub> from AGR is compressed and then mixed with the produced ammonia before entering the urea synthesis reactor. The urea synthesis is based on the decomposition of ammonium carbamate as shown in the following reactions:



The reactor effluents are separated from the non-reacted reactants, which are recycled back to the reactor. The produced urea is purified and finally granulated or prilled.

As mentioned above, the adopted scheme is a “carbon capture ready” plant to minimize the CCS retrofit modifications cost. For this reason the gas turbine and AGR do not need any changes when the plant shifts to the CCS configuration.

### Performance data

The performance data of the two alternatives are summarised in Table 1.

**Table 1** – Performance data.

Case	Fuel	Methanol / Urea production	GT Power Output	Gross Power Output	Aux. Loads	Net Power Output	CO <sub>2</sub> emission	Overall carbon removal efficiency *
	t/h	t/d	MWe	MWe	MWe	MWe	t/h	%
IGCC-MeOH	474.5 coal	5,000	305.0	563.3	309.1	253.7	782.8	26.8
IGCC-MeOH with CCS	474.5 coal	5,000	305.0	563.3	350.5	212.4	183.5	82.8
IGCC-Urea	174.8 petcoke	3,400	150.6	303.5	170.6	132.6	414.6	20.0
IGCC-Urea with CCS	174.8 petcoke	3,400	150.6	303.5	192.5	110.8	70.6	86.4

\* Including carbon present in the chemicals (methanol or urea) produced.

## Investment cost estimate

The investment cost estimate for the four alternatives is reported in Table 2. Figures represent the total investment cost, including EPC and owner's costs of the base case and the delta required to make the capture of the CO<sub>2</sub>.

**Table 2** – Total Investment cost data.

CASE	Total Investment Cost 10 <sup>6</sup> €
IGCC-MeOH	2051
IGCC-MeOH with CCS	+36
IGCC-Urea	1558
IGCC-Urea with CCS	+26

## Production costs

The following Table 3 provides the cost of electricity (COE) for the different alternatives. The cost of electricity has been evaluated on the basis of the following main assumptions:

- Cost of coal: 85 €/t (source: [www.cbs.nl](http://www.cbs.nl))
- Cost of petcoke: 35 €/t
- Price of methanol: 380 €/t. This is the international market average price during the period 4<sup>th</sup> quarter 2007 – 2<sup>nd</sup> quarter 2008. (Note 1)
- Price of urea: 260 €/t. This is the international market average price during the period 4<sup>th</sup> quarter 2007 – 2<sup>nd</sup> quarter 2008. (Note 1)
- Price of sulfur: 240 €/t - 1<sup>st</sup> quarter 2008.  
(source: [www.mjunction.in/market\\_news/sourcing/sulphur\\_price\\_peaks.php](http://www.mjunction.in/market_news/sourcing/sulphur_price_peaks.php))
- No solid by-products cost/revenue is considered.
- No carbon tax penalty is applied to base cases.
- 7,621 equivalent operating hours (reference: 100% capacity) corresponding to 87% equivalent availability.
- Total investment cost as given in Table 2.
- 10% discount rate on the investment cost over 25 operating years.
- Maintenance cost equivalent to approx 3.0% of the total capital costs.

Note 1 : Nitrogen+Syngas Journal, no. 295, September/October 2008

**Table 3 – Cost of electric power production**

CASE	MeOH/Urea prod., t/d	Cost of Coal/Petcoke €/t	Cost of MeOH/Urea €/t	C.O.E. cent€/kWh
IGCC-MeOH	5,000	85	380	3.6
IGCC-MeOH with CCS	5,000	85	380	4.7
IGCC-Urea	3,400	35	260	2.8
IGCC-Urea with CCS	3,400	35	260	3.9

### Sensitivity Analysis

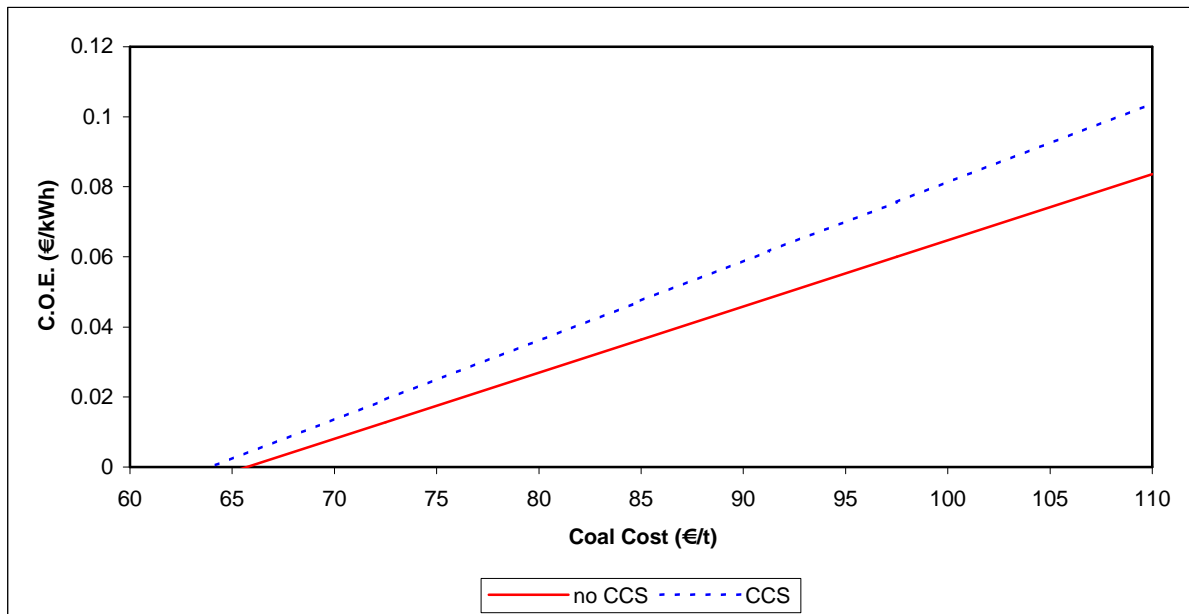
The following sensitivity analyses have been performed for both alternatives:

- COE versus feedstock price variation:
  - coal from 60 to 110 €/t, without and with CCS (Figure 3);
  - petcoke from 20 to 50 €/t, without and with CCS (Figure 4);
- Cost of electricity versus cost of chemicals:
 

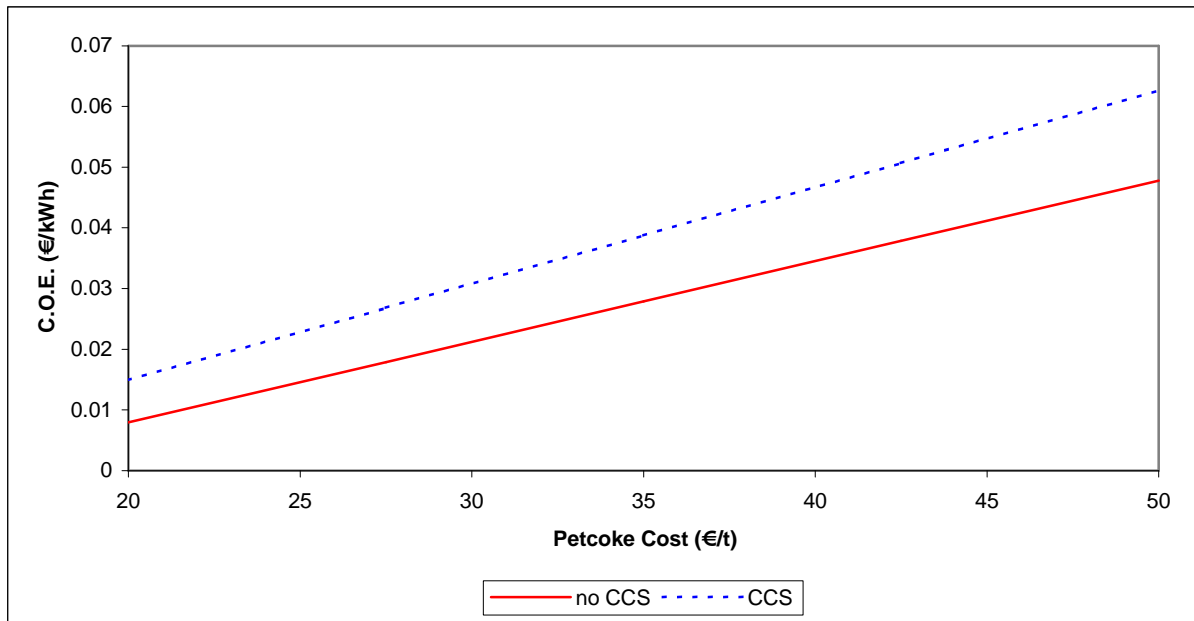
Because of the continuous and significant fluctuation of methanol and urea prices, a sensitivity analysis is performed:

  - Methanol: 250 to 450 €/t (range based on international market month spot price 4Q 2007 – 2Q 2008), without and with CCS (Figure 5);
  - Urea: 230 to 300 €/t (range based on international market month spot price 4Q 2007 – 2Q 2008), without and with CCS (Figure 6);
- Carbon tax from 0 to 40 €/t of CO<sub>2</sub> emitted, without and with CCS (Figures 7 and 8). CCS cases based on a CO<sub>2</sub> transport/storage cost of 10 €/t.

Figure 3 and Figure 4 show the increase of COE at increasing feedstock cost (coal and petcoke respectively).

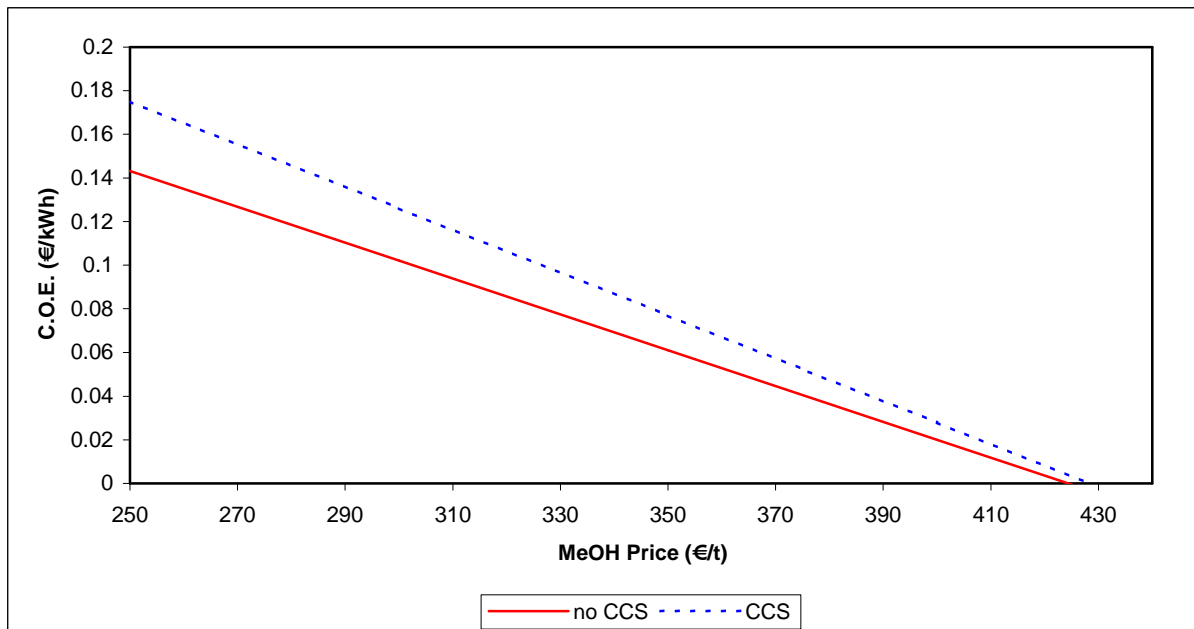


**Fig. 3 – IGCC-MeOH case C.O.E. vs. Coal Cost**

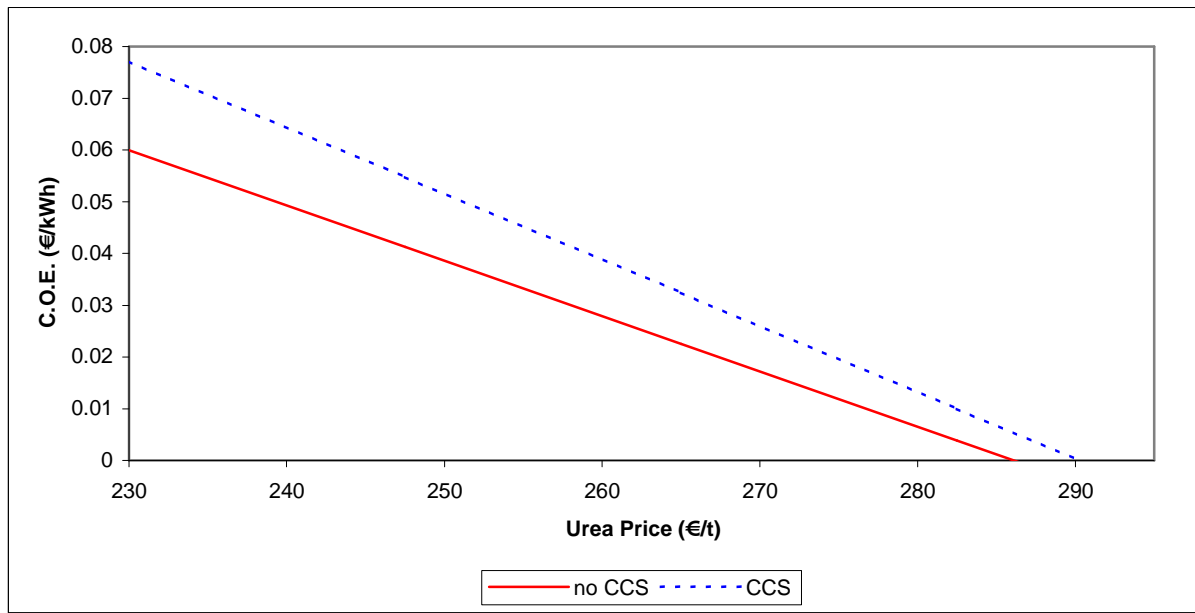


**Fig. 4** – IGCC-Urea case C.O.E. vs. Petcoke Cost

Figure 5 and 6 show the COE vs the chemical product price (methanol and urea respectively). It may be noticed that, over a certain price of methanol and urea, the investment returns from chemicals sales give power production “free of charge”: in other words, revenues from chemicals sales are sufficient to repay the whole plant complex. By applying a certain COE, the IRR is more than 10%.

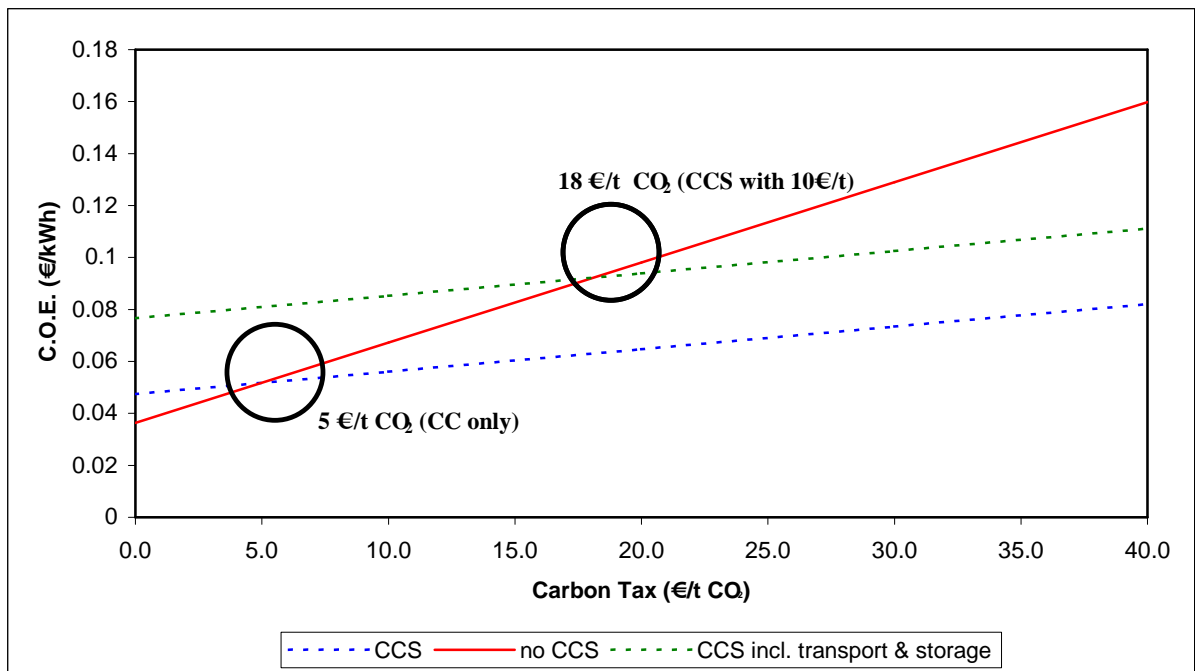


**Fig. 5** – IGCC-MeOH case C.O.E. vs. MeOH Price

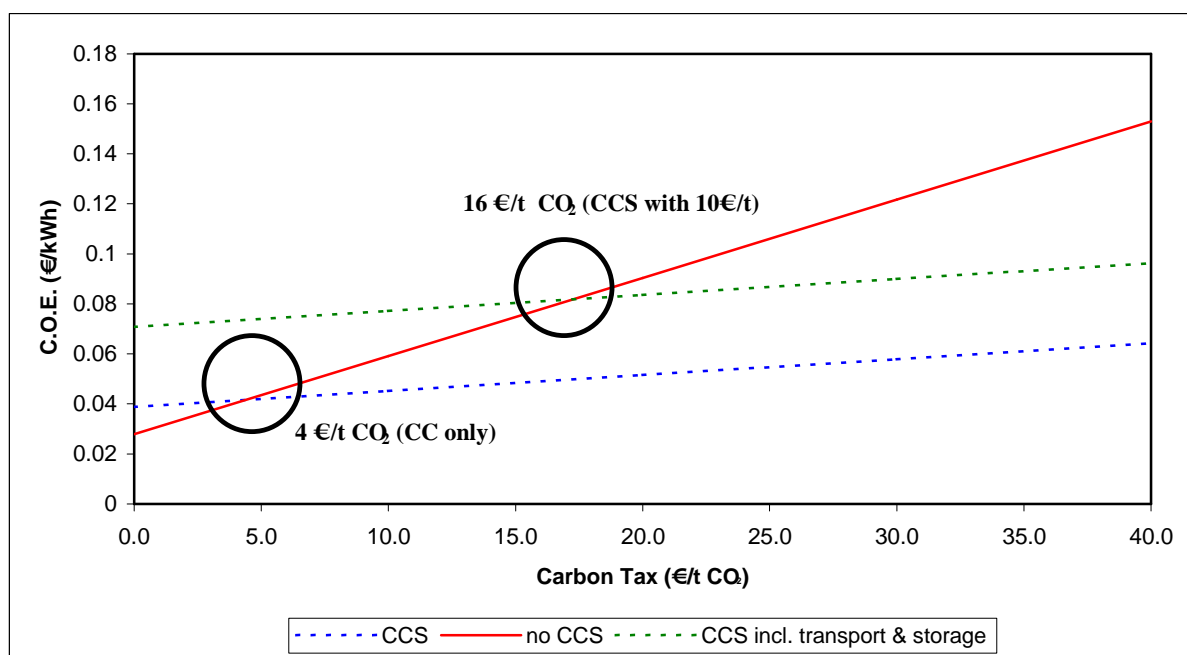


**Fig. 6 – IGCC-Urea case C.O.E. vs. Urea Price**

The previous simulations do not take into account the CO<sub>2</sub> emission penalty. These last graphs (Figure 7 and 8) show that the plants with CCS are economically attractive above an hypothetical carbon tax value of 18 €/t of CO<sub>2</sub> emitted for the IGCC-MeOH and 16 €/t for the IGCC-Urea. The basis is a cost of 10 €/t for CO<sub>2</sub> transport and storage. If transport storage costs are offset by revenues from EOR or CBM applications, the values decrease respectively to 5 and 4 €/t.



**Fig. 7 – IGCC-MeOH case - C.O.E. vs. Carbon Tax**



**Fig. 8** – IGCC-Urea case - C.O.E. vs. Carbon Tax

## Conclusions

The analyses performed in this study lead to the following conclusions:

- IGCC with electric power and chemicals co-production shows an attractive COE, especially for a low value feedstock like petcoke. In fact the petcoke base cost assumption is very conservative; further COE remains competitive for petcoke costs lower than 60 €/t which is an extremely high value.
- The price of chemicals heavily affects the economical evaluation of the plants. A low chemicals price (approx. < 350 €/t of methanol or approx. < 230 €/t of urea for plant without CCS) lead to a COE higher than 6.0 cents €/kWh, which is the current average European value.
- As expected, coal cost affects significantly COE; over a certain feedstock specific cost, the COE reach non-competitive levels (approx. > 98 €/t). However it has to be noticed that these plants are ideally located close to coal mines avoiding transport costs which presently affect significantly the coal cost.
- COE for the IGCC-Urea alternative seems to be less affected by the cost of feedstock and price of chemicals with respect to the IGCC-MeOH alternative.
- CO<sub>2</sub> capture leads to a higher investment cost and to a loss of efficiency with respect to the alternative without CO<sub>2</sub> capture. However an IGCC plant with CO<sub>2</sub> capture is economically viable even at a very low level of carbon tax (> 18 €/t for IGCC-MeOH and > 16 €/t for IGCC-Urea, assuming 10 €/t for CO<sub>2</sub> transport and storage).
- Improvements in the main areas like the gas turbines, gasifiers and ASU are expected in the next years, thus making the IGCC alternative more and more attractive.

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