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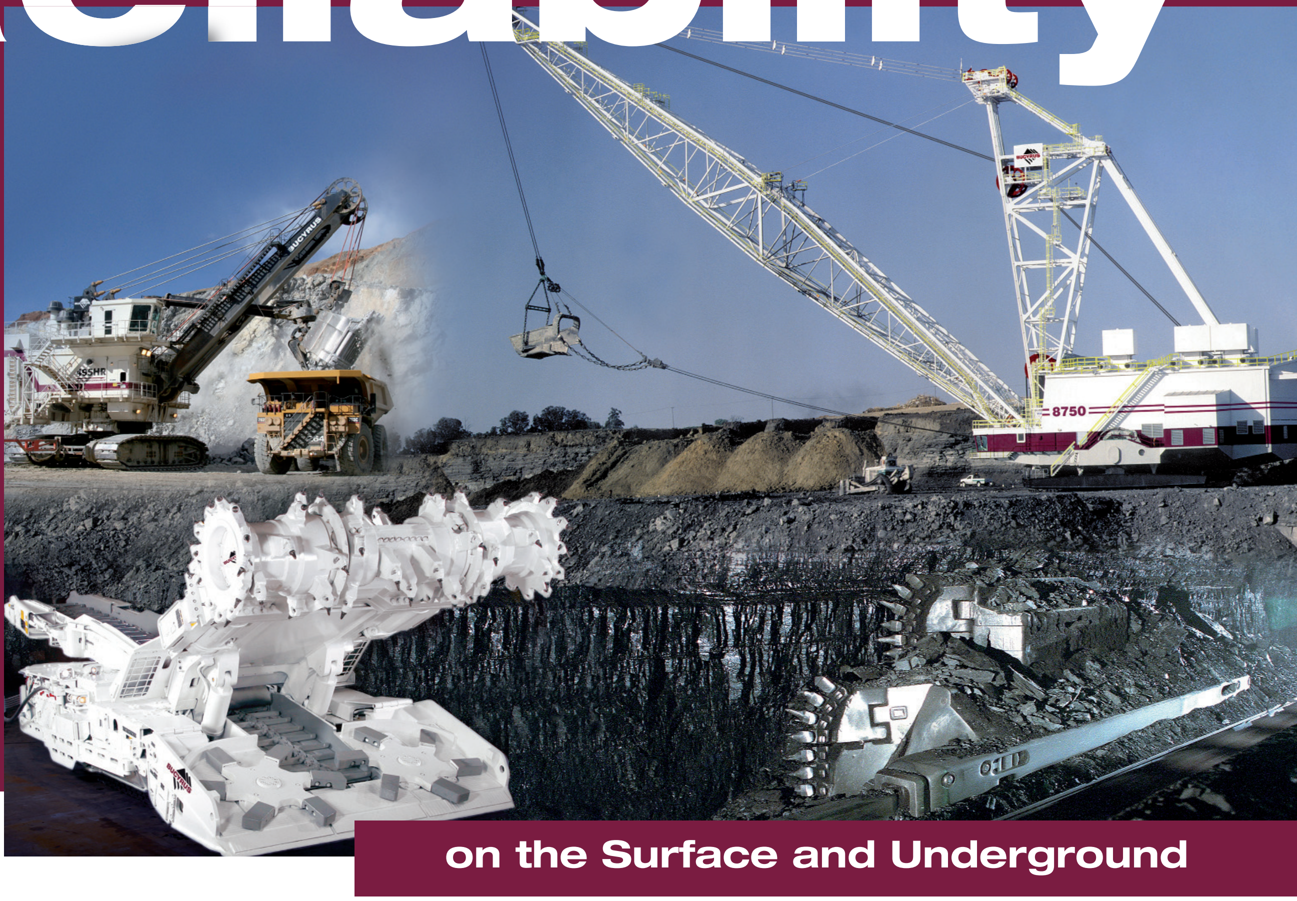

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Economic viability of in-situ coal gasification with downstream CO_2 storage

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Global energy supply is now facing a new set of challenges, due primarily to the soaring world population and the resulting urbanisation and industrialisation of the threshold countries and emerging nations. Bridging technologies based on fossil fuels will have to meet the energy needs of central Europe and indeed the rest of the world until mankind effectively completes the conversion to renewable energy forms. If these technologies are to be generally accepted and successful implemented they will not only have to meet the sustainability criteria associated with the European Union's environmental targets but also fulfil the requirements for economic viability.

Worldwide coal reserves with a supply potential of several hundred years can secure future energy supplies. Because of deep-lying thin seams or faulty geological conditions coal production in Germany is subject to increased cost pressure, so that the present dependence on imports for primary energy sources will continue to increase. Underground gasification (UG) can offer an economical and effective approach to deposit development and utilisation. The planned complete process is based on the development of the coal deposit with the aid of directional boreholes into seams and subsequent in-situ conversion of the coal into a synthesis gas. This synthesis gas is conveyed to the surface via a production borehole and converted into electricity in a gas and steam turbine process (GaS). Reduction of the CO_2 emissions of the complete process is realised by CO_2 separation connected to the power station and subsequent storage (CCS) in the already converted seams. An electricity generation cost model taking into account all relevant parameters from the partial processes was developed in this study for analysis of the cost-effectiveness of the coupled process (UG – GaS-CCS). Furthermore, the competitiveness of the UG-GaS-CCS process was compared with other energy generating technologies suitable for the base load supply in Europe.

Global reserves of coal and lignite have the potential to meet our primary energy needs for several hundred years. At current rates of usage, for example, Germany's coal deposits will be sufficient to meet the nation's solid-fuel needs for some 300 to 400 years. Of course ever deeper workings and difficult geological conditions will tend to pose problems as far as the economic extraction of these resources by conventional mining methods is concerned. Moreover, burning fossil fuels creates the greenhouse gas CO_2.

Given these constraints the technique of in-situ coal conversion – also known as underground coal gasification (UCG) – can be a cost-effective and sustainable solution to the problem of how best to exploit German coal reserves. UCG is based on the concept of "borehole mining", whereby in-seam directional holes are drilled into the coal seam for the injection of an oxidation agent. The resulting sub-stoichiometric conversion process produces a synthesis gas that can be pumped to the surface via a production well. This gas can then be converted into electricity via a combined cycle power plant, or can be used for the recovery of hydrogen or methanol.

The separation of the CO_2 resulting from the two sub-processes, and its long-term storage in underground geological deposits (CCS, carbon capture and storage), can be included in the process in order to meet the sustainability criteria laid down as part of the international climate protection targets. To achieve this the CO_2 can be injected into post-UCG geological deposits via the existing production wells.

This study seeks to examine how in-situ coal conversion operating in conjunction with a combined cycle power plant (CCPP) can be integrated with geological CO_2 storage (UCG-CCPP-CCS) to create an economically viable and competitive player on the European energy market. A coupled calculation model has now been developed for this purpose in order to examine the relevant variables as they affect the power generation costs of the entire process. A sensitivity analysis was also carried out of those parameters that have a significant impact on the electricity production costs and CO_2 emission levels of the overall process.

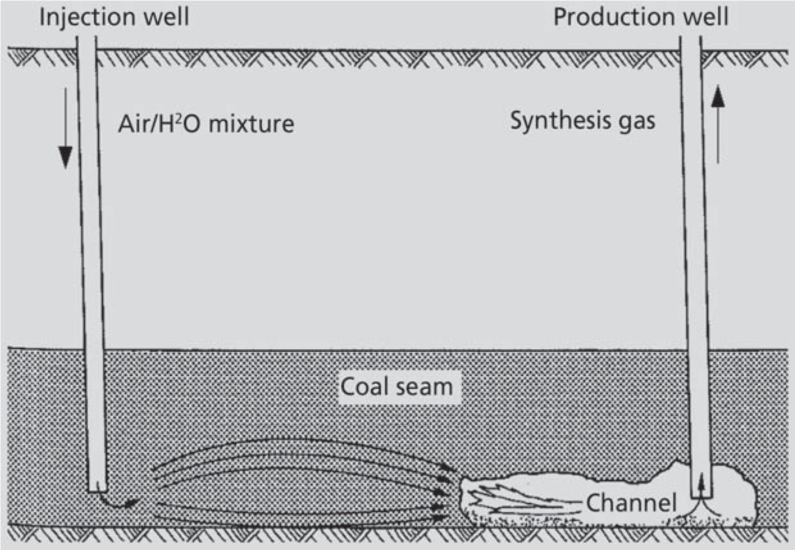

Figure 1. The reverse-combustion principle, modified according to (4).

Background

The idea of underground coal conversion was first mooted in the 19th century and has been continuously developed to its current technical status (1, 2). More than fifty UCG pilot trials were carried out around the world, with more than thirty taking place in the USA (1,3). The first proposals for in-situ coal conversion can be traced back to the German scientist Sir William Siemens, who in 1868 presented an idea for the control and exploitation of underground coal fires.

At about the same time the Russian chemist Dimitri Mendeleyev developed a system for the controlled spontaneous combustion of coal using vertical wells. In 1928 the first national UCG programme was launched in the former Soviet Union and was pursued for another fifty years and more. The USA subsequently began its UCG operations in 1960. However, the availability of favourable alternatives tended to inhibit any large-scale use of the UCG process. The energy crisis of the 1980s then led to a revival of UCG (1) and in 1980 the People's Republic of China launched its first UCG pilot project.

Between 1974 and 1989 the European Union funded a number of research projects aimed at the underground gasification of deep coal deposits that could not be recovered by conventional mining methods. As part of this research programme a joint German-Belgian feasibility study was successfully carried out at Thulin in Belgium during the period 1979 to 1988. Various UCG systems, most of which have been set up as pilot projects, are currently running in a number of countries around the world, namely PR China, Uzbekistan, Australia and South Africa (1, 2, 3).

Operating principle

There are two conventional methods for gaining access to underground coal deposits:

- Opencast mining.
- Deep mining.

However, excessively deep seams, tectonic faulting and a thick overburden cover will all impose technical and financial limits on conventional extraction operations (4). Unless there is a change of mind following the Review Clause decisions of 2012 the German coal industry is due to close down for economic reasons in 2018, irrespective of the fact that the German energy sector is highly reliant on imported fuel and the country still has huge reserves of coal as yet untouched (5).

Borehole mining, which for years has mainly been used for the recovery of mineral oil and gas, provides the basis for the energy extraction method described in this paper. If well drilling technology is to be applied to the exploitation of solid fuels the coal has to be converted into a gaseous or liquid medium by way of the gasification process (6). Apart from the effects of rock pressure and the deformation characteristics of the coal and surrounding rock, which also have to be taken into account, underground coal gasification is essentially identical to conventional coal gasification in a reactor. This means that process data acquired from the operation of surface reactors can be used for underground gasification systems. The raw product gas obtained from the UCG process can be used as a fuel for power generating stations or for the production of hydrogen and methanol (2). A more recent development in the area of underground coal gasification involves CO_2 separation and its subsequent injection and storage in post-UCG geological structures (7).

Reverse combustion

The reverse combustion process, which is intended to increase the low permeability of the coal seam, constitutes an additional stage in advance of the actual gasification phase (Figure 1). This involves entering the seam via a series of vertical holes drilled 20 to 30 m apart. Combustion is then initiated using air at high pressure in order to create a high-permeability connection between the drillings. This is intended to ensure the transit of the large quantities of product gas required for the gasification process.

The reverse combustion technique is based on the gasification of coal within a channel-shaped zone, whereby gasification takes place in the opposite direction to the flow of gas created by the injected oxidation medium. The reverse combustion method produces channels 60 to 90 cm in diameter through which large quantities of gas are able to flow even without the use of high injection pressures. The oxidation medium comprises a mixture of air, oxygen and steam (8).

Reverse combustion has been used successfully at depths of as much as 400 m and in seams of low rank coal. The German-Belgium trials at Thulin were also originally to feature a reverse combustion stage. However, because of the different reaction characteristics of the coal at the depths involved (the Thulin measures were 860 m below ground) the connecting channels failed to achieve combustion. What is more, with reverse combustion the position and course of the channel cannot generally be controlled, which makes the process unpredictable (1).

During the test run the connection between the injection holes and the production well was therefore created by using a deviated target drilling (CRIP method), which is described below.

Controlled retraction of the injection point (CRIP method)

The CRIP method (controlled retraction of the injection point) is the only industrial-scale technique that is suitable for the gasification of deep-lying coal seams. This is because the development of the gasification process can be steered by controlling the retraction path of the injection point. The process involves introducing a liner into the deviated injection hole, which is itself drilled into the coal and as close as possible to the bottom of the seam. This enables the gasification medium to be introduced at a specific point. If for example the quality of the gas in the reaction chamber should fall because of seam burn-out, heat loss to the surrounding rock or strata collapse a new reaction zone can be established outside this interference sector by triggering another ignition behind the borehole. This process can be repeated until the seam has been completely consumed of coal (1).

According to (1) the CRIP method can also be used for the exploitation of thin seams, where conventional gasification methods tend to fail because of poor process reliability and the absence of any opportunity for improving performance. The preferred gasification medium is a mixture of oxygen and steam, as the inclusion of air would have a negative effect on the quality of the product because of the high nitrogen content. Figures 2 and 3 present a schematic view of how the CRIP method is used to open-up a coal seam.

Nine production fields each with a surface area of 1 km^2 and an average seam thickness of 1.5 m are required to supply fuel to a combined cycle power plant over an operating life of 20 years. The transverse production well (see Figure 3) connects all the injection holes together and acts as a transit route for the synthesis gas produced as a result of the conversion process (8).

CO_2 storage in post-UCG seams

The CO_2 produced above ground as part of the UCG-CCPP-CCS process can be stored long-term in post-gasification geological structures using the principle depicted in Figure 4. Investigations into CO_2 injectivity, migration and storage reliability are currently being carried out by (9). CO_2 storage in gasified seams is certainly a worthwhile proposition from an economic viewpoint, as the borehole infrastructure used for the UCG processes can be re-used for CO_2 injection, which means that no additional drilling costs are incurred. The

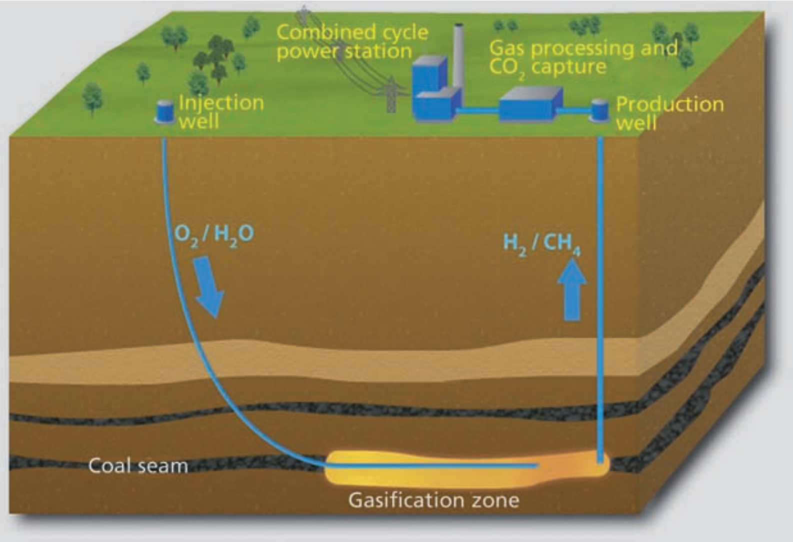

Figure 2. Principle of in-situ coal gasification based on the CRIP method.

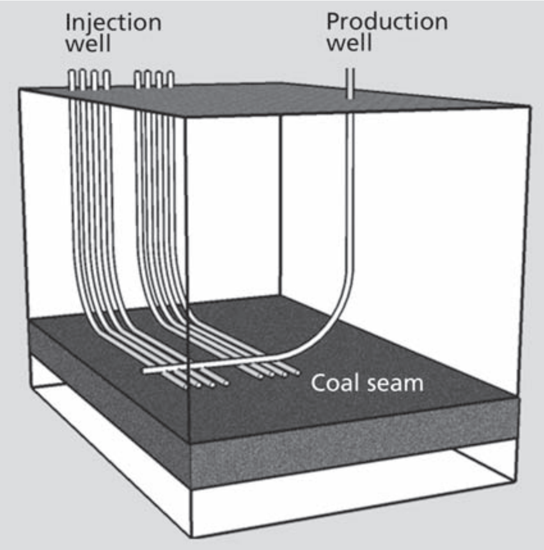

Figure 3. Schematic representation of the layout of the injection and production wells.

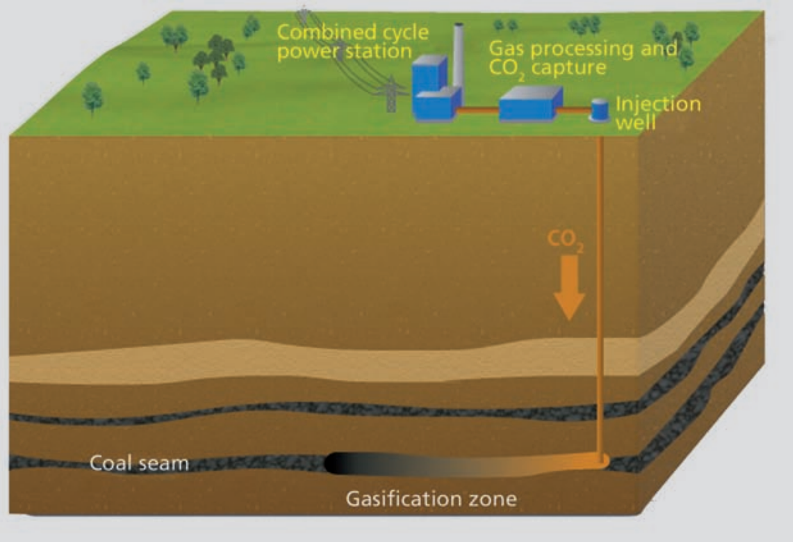

Figure 4. Principle of CO_2 storage using post-gasification coal seams.

Table 1. Coal reserves and resources and primary energy consumption in Germany, the EU-27 and worldwide according to (5), (10), (11) and (12).

	Germany	Europe	World-wide
Reserves [Gt]	0.16	19.2	7.36
Resources [Gt]	84.5	479	8,818
Primary energy consumption	0.47	2.45	11.5

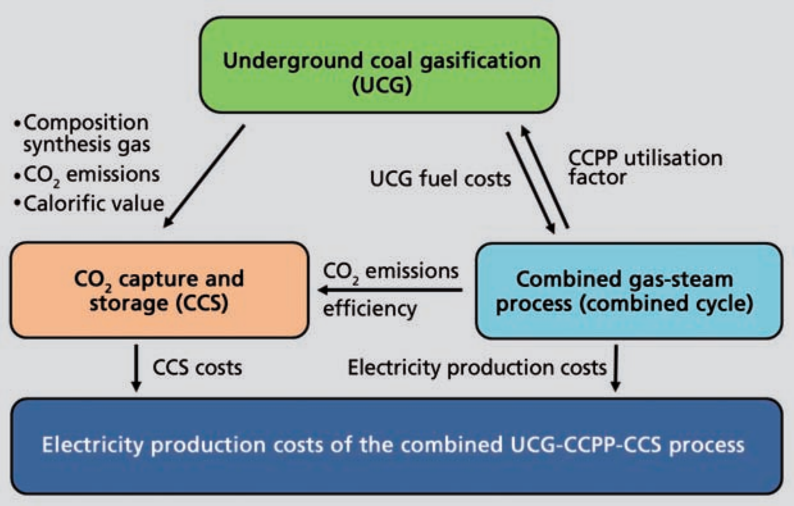

Figure 5. Coupled model for calculating the power production costs of the UCG-CCPP-CCS process.

cost of CO_2 separation and reservoir monitoring is discussed below.

Potential

Assuming an average production of 2,700 m^3 of synthesis gas per tonne of gasified coal (1), an average calorific value of 12.5 MJ/m^3 of synthesis gas (8) and an exploitation factor of 30 % of the coal reserves presented in Table 1 it is calculated that the gas obtained from in-situ coal gasification could fully replace the primary energy fuels currently being used in Germany for a period of more than 62 years. From a European perspective, and under the given boundary conditions, this period would extend to more than 68 years, while in global terms the figure becomes 267 years. All three scenarios assume constant primary-energy consumption throughout the total exploitation period.

On this basis in-situ coal gasification in Germany could in theory reliably cover the nuclear energy gap – with the country set to close down its nuclear power industry (in 2007 nuclear energy was responsible for 11 % of primary energy consumption) – for a period of more than 570 years. If UCG energy were in addition to be used in place of oil (33.6 % share of primary energy consumption in 2007) it could provide a theoretical coverage lasting more than 140 years. This would give Germany an adequate time window to develop and implement a primary-energy supply system based mainly on renewables.

Efficiency analysis

In order to assess the economic viability of such an operation the specifications were laid down for a reference power plant in which the synthesis gas obtained from underground coal gasification was converted into energy using a combined cycle generation process. The following operating conditions were applied to the overall process: UCG was based on the CRIP method using an oxygen-steam mixture with a 55 % oxygen content as the oxidation agent (1). According to (13) the net efficiency level of the CCPP is 58 % when operating at full load of 7,500 h/a and at a net output of 600 MW_{el}.

In order to ensure that the CC power plant can operate at peak load the net output of the model is dynamically adapted to the available fuel supply from the UCG operation as a function of the boundary conditions. According to (1) this reference scenario will produce about 306,000 Nm^3/h of synthesis gas with an average calorific value of 12.5 MJ/m^3 (8). The UCG operation has a 95 % availability rate (2). CO_2 storage costs also include the monitoring of the storage reservoir and are added on a pro-rata basis to the power generation costs.

Below is a description of the method used for calculating power generation costs on the basis of the models that have been developed for the purpose. These are based on a calculation model for the power generation costs of a CC power plant according to (14) and (15), a UCG model developed specifically for this study that uses data from (1), (2), (4), (8) and (16) and a CCS model that uses data from (17). Figure 5 presents the different models and their interfaces.

Calculation model
Power generation costs

Modern combined cycle power stations, which use a gas and a steam turbine, deliver outputs of between 350 and 400 MW_{el}. By combining two gas turbines with a steam turbine it is possible to obtain outputs of 800 MW_{el}.

Table 2. Boundary conditions for the calculation model of the electricity generating costs of the combined cycle power station.

Net output of combined cycle power stations [MW_{el}]	600
Construction time for combined cycle power stations [months]	24.0
Nominal calculated interest rate for CCPP demolition/retrofitting costs [%]	6.0
Nominal calculated interest rate for CCPP construction time [%]	11.0

The advantages of CCPP are that they produce up to 50 % fewer CO_2 emissions compared with equivalent coal-fired power stations, are more cost effective (lower manpower requirement, higher efficiency levels and lower investment costs) and only need two-thirds of the start-up time of conventional coal-fired plant (13). The economic risks associated with CCPP stem mainly from the fact that fuel costs make up about 60 % of the total power generation costs, which means that such installations are very much dependent on developments in gas price levels (13, 18).

In the analysis presented here this factor does not constitute such a risk because the fuel required for power generation is produced in the interconnected UCG process. The cost of the UCG process therefore has a major influence on the power generation costs, which for the purpose of this study have been calculated using the models presented in (14) and (15). In this case the boundary conditions are as presented in Table 2. The power generation costs were also calculated as average costs using the full costing principle and all figures were deflation-adjusted and presented exclusive of VAT.

Here the efficiency level is the most important optimisation parameter for grading the effectiveness of a power station, as this factor will determine both the investment costs and the fuel consumption rate. Improving the efficiency level means that savings can be made on fuel costs, as the fuel conversion process becomes more effective. Increasing plant efficiency usually requires additional investment costs. In the reference scenario used here the efficiency of the CCPP is 58 % (15). The overall process with CO_2 capture and storage (UCG-CCPP-CCS) has an efficiency level of about 39.8 % (16). The fuel costs are essentially dependent on the marginal operating conditions of the UCG process.

Calculation model
In-situ coal gasification

The cost of an underground coal gasification project is calculated from the drilling costs and the operating costs of the UCG system that supplies fuel to the combined cycle power station. Tables 3 and 4 present the different values and assumptions used for the calculation process.

The most significant cost item in any UCG operation will be the drilling work (see Table 3). Drilling costs will in fact make up about 62 % of the total cost of the UCG process. In the reference scenario being examined here this cost factor was included on the basis of 3,000 € per meter of drilling. This deliberately conservative figure was chosen in order to allow for the additional cost of including temperature-resistant and CO_2-resistant borehole casings.

The total drilling costs were calculated using the length of the wells and the number of drillings. With each hole set 40 m apart a total of 26 wells will be needed to develop the target deposits. Assuming a gasification depth of up to 2,000 m, an average in-seam drilling distance of 1,000 and an average deviated hole length of 1,080 m (at a deviation of 2 to 3° per 30 m of drilling), along with one transverse connection per gasification zone (production well), the total drilling costs amount to 2.39 bn. €.

Table 4 presents a summary of the costs that have to be taken into account in the UCG study, together with the relevant energy parameters. Assuming 95 % plant availability according to (2) the total costs work out at 3.63 bn. .

Fuel consumption

The annual fuel consumption rates are calculated on the basis of net electrical output, the number of full-load hours and the net efficiency level of the plant. In the reference case presented here this results in 27.93 PJ/a, which equates to 559 PJ after 20 years of operation. The fuel production from the UCG operation and the fuel consumption level of the CCPP are dynamically compared in order to

Table 3. Calculated assumptions and boundary conditions for the UCG-CCPP-CCS refernce scenario.

Item	Value	Source
Drilling costs [€/m]	3,000	assumed
Depth of the deposits [m]	2,000	assumed
Average seam thickness [m]	1.5	(1)
Number of seams	1	assumed
Well to well interval [m]	40	(1)
Area of UCG zone [km²]	1	(1)
In-seam drilling distance [m/hole]	1,000	(1)
Number of wells/UCG zone	26	calculated
Number of zones	9	(1)
Total number of wells	234	calculated
Total drilling distance [m]	795,600	calculated
Total drilling costs [bn. €]	2.39	calculated

Table 4. Total costs of the UCG process.

Item	Value	Source
Drilling costs for a seam depth of 2,000 m [bn. €]	2.39	calculated
Cost of land acquisition [€/m²]	7.10	(8)
Land requirement [km²]	9	(1)
Total cost of land acquisition [Mill. €]	63	calculated
Pipework, measurement and control equipment [Mill. €]	568	(8)
Production of gasification agent, gas processing [Mill. €]	612	(8)
Percentage share of drilling costs [%]	62	calculated
Total costs [bn. €]	3.63	calculated

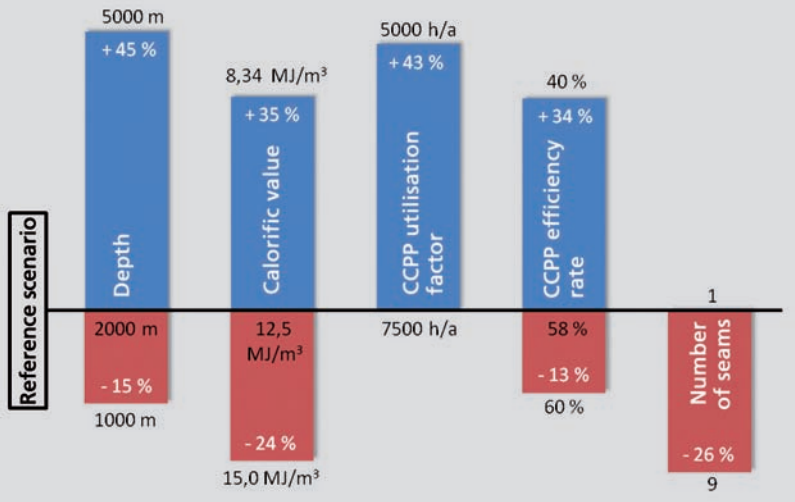

Figure 6. Impact of relevant model parameters on the power production costs of the UCG-CCPP-CCS process.

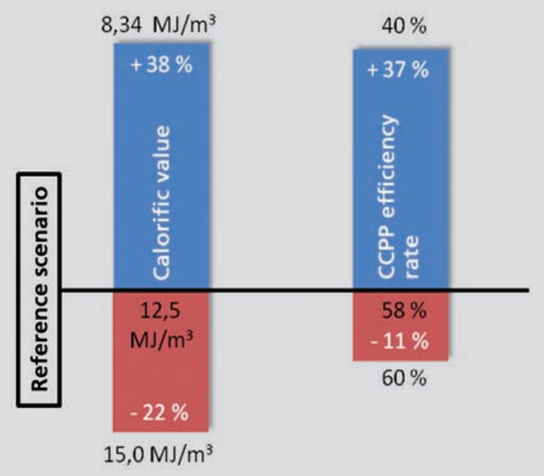

Figure 7. Impact of relevant model parameters on CO_2 emissions from the UCG-CCPP-CCS process.

determine the overall fuel costs. In the reference model the fuel costs from the UCG system will account for 58 % of the power generation costs, whereas in a conventional combined cycle power station the fuel costs will normally make up about 75 % of the electricity generating costs (15).

Calculation model CO_2 capture and storage monitoring

Both the UCG operation and the CCPP process will generate CO_2 emissions. The quantity of CO_2 that can be captured from the synthesis gas produced as a result of the UCG operation will vary according to the chemical composition of the product gas. In our reference scenario the calculations are based on a product-gas composition as described in (1) and an achievable CO_2 capture rate as presented in (17).

The interconnected CO Shift Process also contains quantities of carbon dioxide, which have to be added to the 1.92 Mill. t CO_2/a contained in the synthesis gas. The carbon monoxide contained in the product gas is converted into CO_2 by combustion at 850 °C, thereby producing 13,000 t of CO_2/a. The UCG process produces a total of 1.93 Mill. t CO_2/a by this means. Additional CO_2 emissions are generated by the conversion of methane contained in the synthesis gas. At a plant utilisation rate of 7,500 h/a some 0.84 Mill. t CO_2/a will be produced from this source. The combined UCG-CCPP process will therefore generate a total of 2.76 Mill. t CO_2 a year and will as a result produce 55.3 Mill. t of CO_2/a over a operating life of 20 years. In our reference scenario the CO_2 emission rate amounts to 0.614 t CO_2/MWh, which is comparable to that of a gas-fired combined cycle power station.

The extended control and monitoring programme presented in (17) was chosen for the coal deposits intended for CO_2 sequestration in our reference scenario. As well as monitoring seismic and microseismic movements and injection rates this programme also features highly developed technology capable, for example, of measuring the flow of CO_2 at the surface storage facility. This programme would cost 0.2 €/t of stored CO_2, which for the emissions generated in the current reference case would equate to 0.55 Mill. €/a, or 10.96 Mill. € over a total operating period of 20 years.

Sensitivity of power generation costs and CO_2 emissions from the UCG-CCPP-CCS process

A sensitivity analysis was undertaken in order to determine how the boundary conditions used in the present scenario affect the power generation costs of the combined calculation model. To this effect various parameter variations were assessed, namely:

- Depth of the deposits.
- Calorific value of the synthesis gas.
- CCPP efficiency rate and utilisation factor.
- Number of seams.

The results of the sensitivity analysis are presented in Figures 6 and 7.

In Germany the coal deposits that would be considered suitable for underground coal gasification lie at depths ranging from 1,000 to 5,000 m. Figure 6 shows how the depth of the coal measures affects the development of power generation costs. Variations in the depth of the deposits will alter the power production costs by about 15 % for each additional 1,000 m.

Figures 6 and 7 also show how the calorific value of the synthesis gas impacts on the power generation costs and the emission levels. An increase from 12.5 to 15.0 Mill. J/m³ will reduce CO_2 emission levels by about 22 % and at the same time cut generating costs by 24 %.

While in terms of the CCPP utilisation factor of 7,500 h/a no significant deviations from the standard operating routine can be expected, a 2 % increase in the CCPP efficiency rate will reduce power generation costs by 13 % and will at the same time cut CO_2 emission levels by about 11 %.

The number of usable coal seams also has an impact on the power generation costs as money can be saved on drilling expenditure by exploiting several superimposed seams. When nine superimposed seams with an average seam interval of

50 m are accessed using the same vertical wells the power generation costs fall by 26 % compared with the reference scenario (see Figure 6).

Competitiveness on the European energy market

Figure 8 presents a comparison of power generation costs and CO_2 emissions for base-load power stations currently operating in Europe.

The power generation costs for the reference scenario without CO_2 capture amount to 29.34 €/MWh at a CO_2 emission rate of 0.614 t/MWh. If 50 % CO_2 capture and storage is achieved the power generation costs of the reference project increase to 35.34 €/MWh. This makes the generation costs about 24 % lower, and the CO_2 emission rate about 12 % lower, than the equivalent figures for a natural gas-fired combined cycle power station.

If the CO_2 capture and storage rate is raised to the current technically best achievable level for CCPP of 86 %, according to (17), the power generation costs for the reference scenario increase to 39.67 €/MWh and the CO_2 emission rate falls to 0.086 t/MWh. As far as CO_2 emissions are concerned the reference case produces results that are comparable with those of a nuclear power station, whereby the power generation costs of the UCG-CCPP-CCS process are about 36 % lower.

Summary and discussion

Underground coal gasification could well provide a sustainable answer to the problem of how best to exploit coal deposits that cannot at present be recovered economically, especially in central Europe. This technique would also significantly reduce our reliance on primary fuel imports. Coupling the gasification process to subsequent CO_2 storage in post-UCG deposits would at the same time open up new possibilities for the eco-friendly exploitation of these reserves. By considering various energy scenarios the application of UCG-CCPP-CCS technology could replace Germany's current primary fuel requirements for a period of up to 570 years, thereby creating a potential bridging technology for new energy production concepts.

A combined calculation model was developed for the purpose of evaluating the economic viability of the total UCG-CCPP-CCS process. On this basis a sensitivity analysis was carried out in order to assess the key parameters as they affect the development of electricity production costs and CO_2 emissions for the entire process. This study identified the following parameters as being the main influencing factors:

- Depth of the deposits.
- Calorific value of the synthesis gas.
- CCPP efficiency rate and utilisation factor.
- Number of superimposed/usable seams.

The total process is capable of competing economically with any energy production technology currently used for base-load supply on the European market, while substantially lower power generation costs can be expected for an equivalent level of CO_2 emissions.

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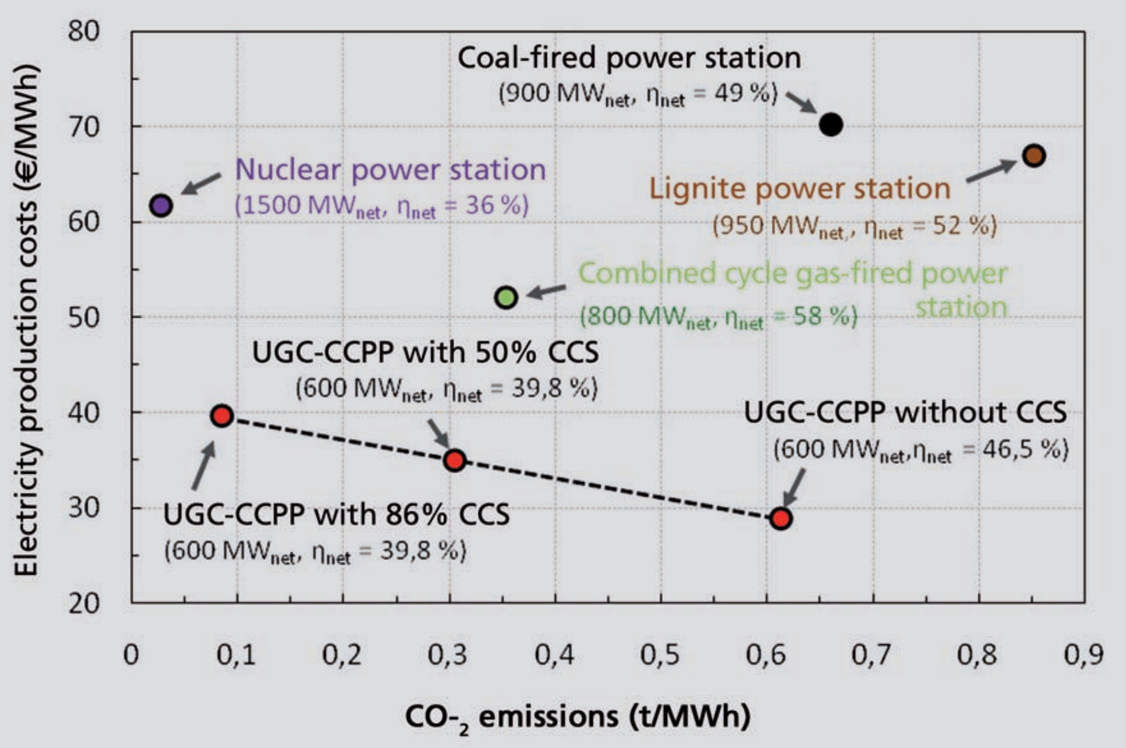

Figure 8. Power production costs and CO_2 emissions for the UCG-CCPP-CCS process compared with other European base-load power stations, basic data deflation-adjusted and updated according to (14), (15), (16) and (17).

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