Gampe, U.; Hellfritsch, S.; Gonschorek, S.: Oxyfuel Technology for Fossil Fuel-fired Power Plants with Carbon Sequestration - Technical and Economic Feasibility. In: ENERDAY Workshop on Energy Economics and Technology. Dresden, 2006

OXYFUEL TECHNOLOGY FOR FOSSIL FUEL-FIRED POWER PLANTS WITH CARBON SEQUESTRATION – TECHNICAL AND ECONOMIC FEASIBILITY

Prof. Dr.-Ing. Uwe Gampe
Dipl.-Ing. Stefan Hellfritsch
Dipl.-Ing. Sonja Gonschorek
Chair of Power Plant Technology, Dresden University of Technology, Germany

Abstract

The commitments made in the Kyoto Protocol and the resulting National Allocation Plan (NAP) for the German energy sector are forcing power plant operators to take measures in reducing their CO_2 emissions. However, there is a dominating position of coal power on the German energy market that cannot be replaced in the near term. For future security of supply, the number of modern coal-fired power plants in Germany will even have to be increased due to the necessary replacement and extension capacity for power generation. Thus, that coal-fired power plants with CO_2 separation could also be an option for the near future. Of course, these concepts should be considered only as a temporary technology.
This paper gives an overview about research and development activities for the so called oxyfuel process with CO_2 separation which currently represents the most promising option for near-term application in power generation processes. With emphasis on the German ADECOS project coordinated by the Dresden University of Technology, an advanced process layout for such a power plant fired with lignite is introduced and the technical and economic feasibility will be estimated.

key words: CO2 separation, oxyfuel, coal, ADECOS

1. Principles of the oxyfuel process with CO_2 recovery

The oxyfuel process, sometimes also referred to as O_2/CO_2 combustion, is characterized by the feed of pure oxygen into the combustion. In order to limit the high flame temperature during combustion with pure oxygen, extensive flue gas recirculation is necessary. This is as it were the replacement of air nitrogen by recirculating flue gas which mainly consists of CO_2. In comparison with the conventional combustion in air atmosphere the flue gas volume at boiler outlet amounts to about 30 % for the oxyfuel process only. Hence, the following components will be less space-consuming than in a conventional power plant.
Within the flue gas treatment process chain, water vapour and inert gases and harmful components like SO_x have to be removed by condensation, scrubbing and phase separation. The remaining flue gas (95% CO_2 purity) is dried and compressed and will then be ready for transportation and storage.
Figure 1 shows a simplified oxyfuel process scheme with CO_2 recovery and coal as fuel.

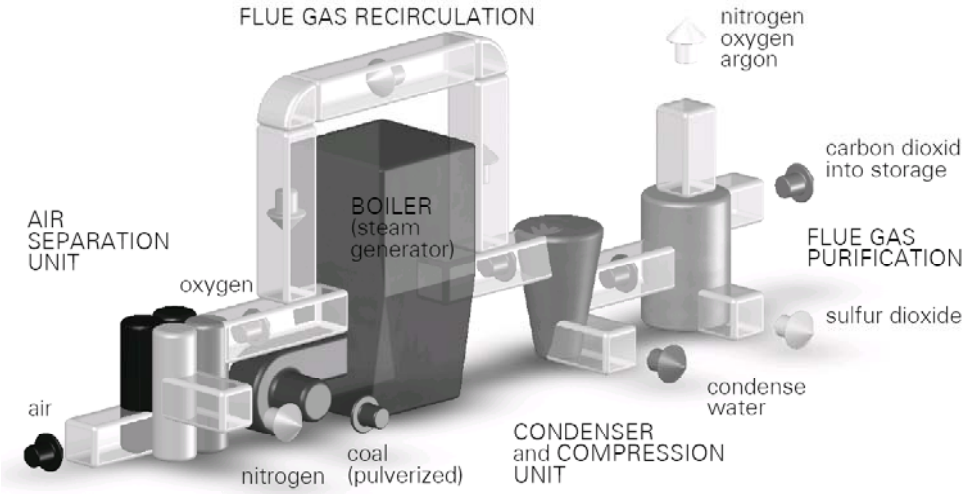


Figure 1: Scheme of an option for the lignite-fired oxyfuel process

The exclusion of air nitrogen aims at producing a flue gas stream with up to 80 % CO_2 concentration, depending on the carbon content of the fuel. The amount of flue gas and the respective composition for different combustion modes are shown in **figure 2**.

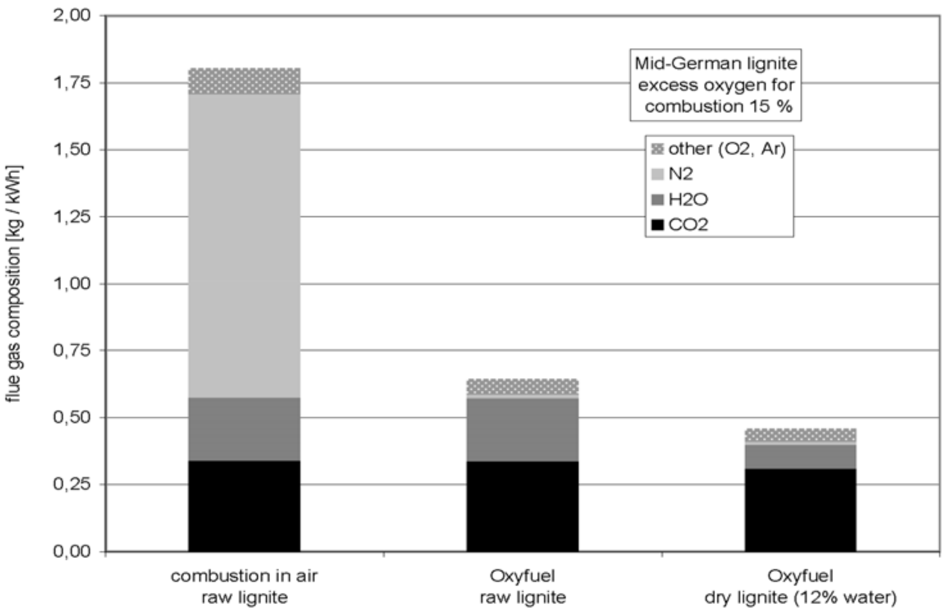
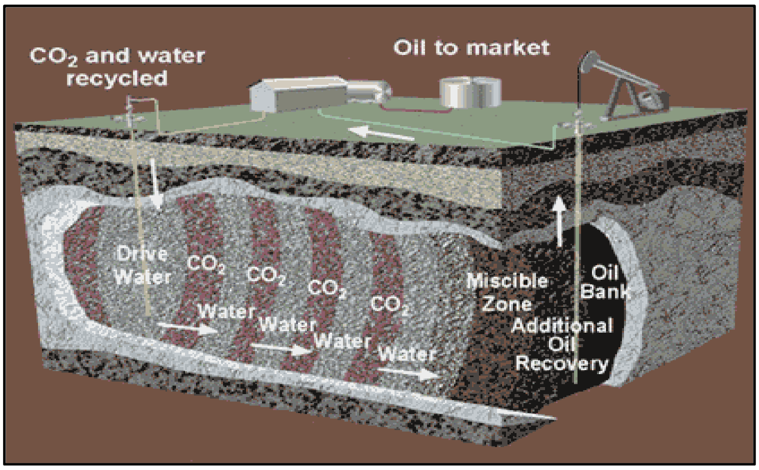


Figure 2: Quantity and composition of flue gas from different coal combustion concepts

2. Long-term CO_2 storage options

The most effective way to store sequestered CO_2 without impact on the atmosphere is the Enhanced Oil Recovery (EOR, injection of inert gases into depleted oil fields to increase the yield). After reaching full depletion of such an oil field it can be sealed and the CO_2 is enclosed safely. However, EOR or similar profitable applications of sequestered CO_2 will not be possible in any place and the storage capacity is limited. Thus, other storage options are also being investigated. One of them is CO_2 storage in deep saline aquifers or similar geologic formations, which offer the highest potential storage capacity in Germany and Europe. **Figure 3** illustrates the EOR case and aquifer storage.



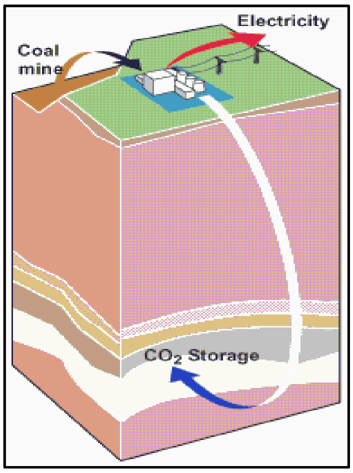


Figure 3: CO_2 for Enhanced Oil Recovery and aquifer storage (Weyburn Project / CO_2 Store)

3. Overview about the ADECOS research project

The ADECOS research project (Advanced Development of the Coal-fired Oxyfuel Process with CO_2 Separation) bundles the activities of 9 partners from industry and universities under the COORETEC framework of the German Federal Ministry of Economics and Technology. The project is co-ordinated by the Chair of Power Plant Technology at the Dresden University of Technology.
Objective of the ADECOS project is the techno-economic assessment of coal-fired oxyfuel processes with CO_2 separation for mid-term application.
This comprises basic research on oxyfuel combustion, flue gas treatment processes, reliability and economic aspects. The oxyfuel process restricts the necessary changes in the today's well-tried and reliable power plant concepts to the combustion and the flue gas path only, which is a benefit. Additional plant components, like air separation unit and CO_2 recovery train, have to be integrated. These technologies are well-known from other sectors of industry, but need to be adapted relating to size and specific process boundary conditions.

4. Technical aspects in the development of coal-fired oxyfuel power plants

Oxygen production

Oxygen for combustion in the process can be supplied via direct refitting of conventional cryogenic air separation units (ASU). This is a mature technology with the disadvantage of a high energy consumption. In order to improve the thermal efficiency of the overall plant concept, deeper integration of the ASU is performed by using the considerable amounts of waste heat from the air compression.

Oxyfuel coal combustion

Basic investigations on oxyfuel combustion of different coals are essentially for the technology development. Tests are performed at a pulverised coal combustion test facility of TU Dresden that was specifically retrofitted for this purpose (**figure 4**) and at a combustion reactor of TU Hamburg-Harburg. These investigations deliver results on necessary oxygen and recirculation ratios, combustion stability, emission behaviour and the influence on slagging and fouling in steam generators.

Figure 4: 50 kW_{th} pulverised coal oxyfuel combustion test facility at the TU Dresden

The parameters derived from these tests can be compared with conventional air-blown combustion and they can be used for modification of the design rules for steam generators.

Furthermore, numerical simulation of the combustion test facility using FLUENT™ code is the basis for the development of a computational combustion model which can be applied to even larger oxyfuel plants. Two examples for simulation results are shown in **figure 5**.

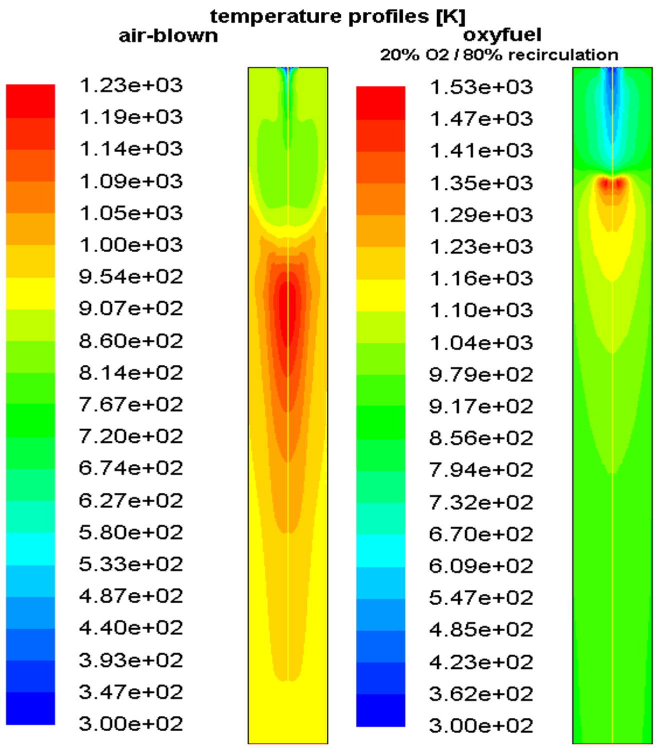


Figure 5: Simulation showing different temperature profiles for oxyfuel and air-blown coal combustion

Coal-fired oxyfuel steam generators

The design of the oxyfuel steam generator is another key point of the ADECOS project. State-of-the-art for coal-fired power plants is a pulverised coal (PC) fired steam generator, which will be the basis also for oxyfuel. Other options to be evaluated are fluidised bed combustion and slag-tap furnace steam generators. Both types seem to have advantages compared to the PC base case, but whatever type of combustion, significant modifications compared to conventional boilers will always have to be made. Most relevant will be a minimisation of leakage air inlet into the boiler in order to avoid air nitrogen in the flue gas. That concerns not only to the boiler itself, but also to the firing system (coal feed, burners) and the following process stages in the flue gas path. Further, an oxyfuel steam generator has to be equipped with a recirculation system, i.e. flue gas and/or bed material in the case of fluidised bed combustion. A possible steam generator design for a 300 MW oxyfuel power plant as part of a preliminary study by Dresden University of Technology is shown in **figure 6**.

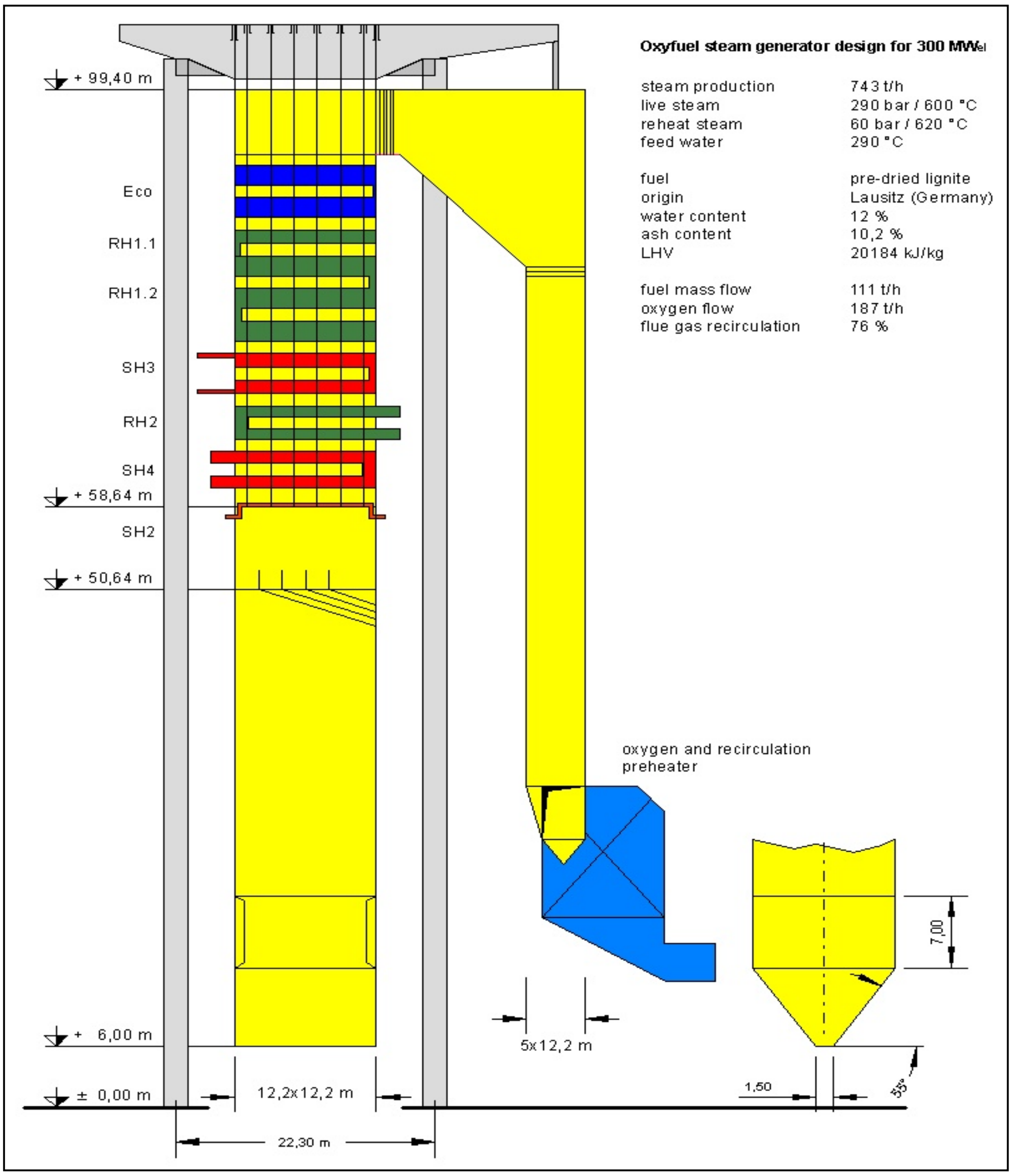


Figure 6: Pulverized coal-fired oxyfuel steam generator from a preliminary design study

For enhanced efficiency of the boiler and the entire process, a specific flue gas recirculation scheme for oxyfuel steam generators with a recirculation preheater was developed at the Dresden University of Technology. It has advantages both compared to a 'cold' and a 'hot' flue gas recirculation scheme and is free of their respective drawbacks (see **figure 7**).

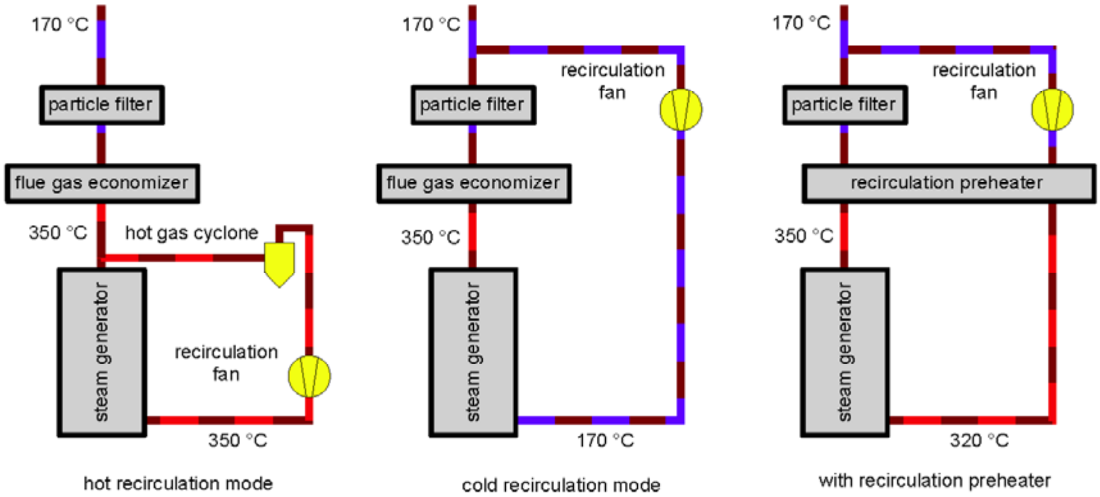


Figure 7: Different flow schemes for flue gas recirculation in an oxyfuel process

Flue gas treatment / CO_2 recovery train

There are also two work packages in the ADECOS project dealing with engineering aspects of a flue gas treatment system specifically designed for the oxyfuel process. The problem is to clean the highly enriched CO_2 flow from water vapour, harmful gases (NO_x, SO_x) and residual gases like nitrogen and surplus oxygen from the combustion process. A purity must be met that makes transport and storage of CO_2 possible and safe, but is still economically justifiable.

The CO_2 recovery train to be designed must have the lowest possible energy consumption. After all, the cleaned gas flow has to be pressurised (mostly supercritical) for transportation and storage.

For the investigation of the flue gas treatment several possible treatment process steps are analysed, combined in a process engineering software ASPEN PLUS and economical calculations are added. In this calculations various combinations of processes with variable parameters can quickly been calculated and a case specific energetically as well as economically optimisation for CO2 recovery train can be found.

The problems that arise during that work come from necessary adaptions of known technology like, for example, the wet flue gas desulphurisation (FGD) with limestone. First experiments have shown that the desulfation efficiency slightly degrades with increasing CO_2 content in the flue gas. Another aspect for the FGD is, that the desulphurisation unit needs an external oxidation of the gypsum pre-products, since air ingress into the flue gas is highly undesirable. This shows that considerable modifications have to be made even to known technologies.

Another problem is the missing material equilibrium data of CO2 with the existing impurities especially in the high pressure range. ADECOS comprises also particular investigations performed in an equilibrium view cell at TU Hamburg-Harburg. From the generated data the calculations of the whole CO2 recovery train calculations will be validated.

Integration of results into complete power plant concepts

Another required step towards possible future power generation based on the oxyfuel process with CO_2 separation is the optimisation of the overall process with all additional components like air separation and CO_2 recovery train. There are many proposals how these could best be integrated. However, an optimum process design must be found considering many factors like overall energy efficiency, the net power output in relation to the gross value as well as separation rate and purity of the CO_2 produced. Further, the common operation criteria for power plants under liberalised market conditions should be met, i.e. start up time, load alternation characteristics and part-load capability. An optimised process scheme from a recent 920 MW oxyfuel study by the Dresden University of Technology is shown in **figure 8**.

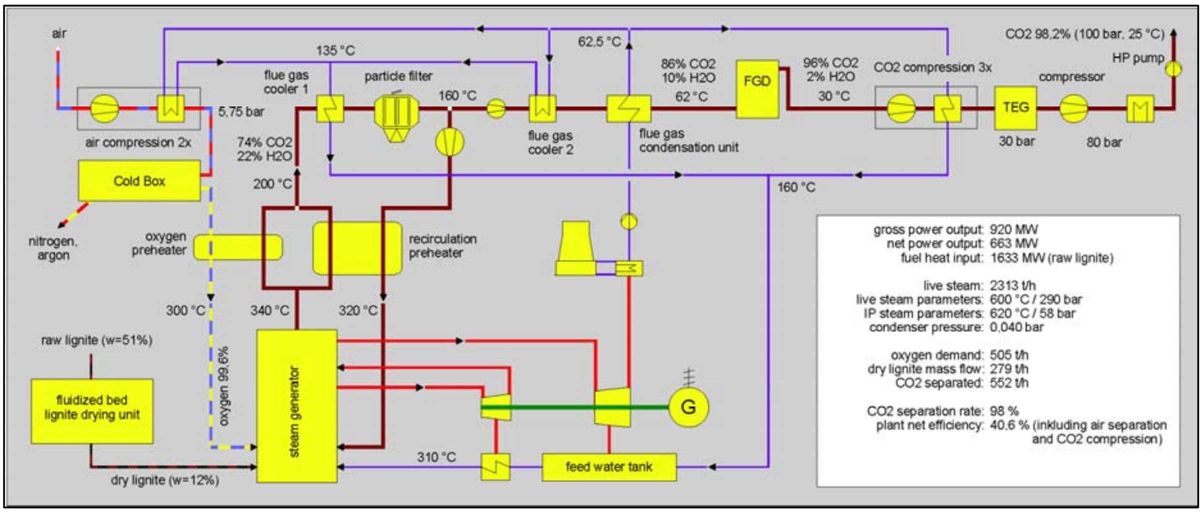


Figure 8: Optimised process scheme for a 920 MW oxyfuel power plant with CO_2 separation

5. Economic evaluation of oxyfuel power plant concepts

Most important during evaluation of new power generating processes is to check the economic feasibility. However, there still exist some parameters that are not easy to estimate today and that could strongly influence the cost effectiveness as they vary over the lifetime of a power plant. In the case of CO_2 separation, this is first of all the revenue from sale of surplus CO_2 certificates to other emissions as well as the transportation and storage costs.

Therefore, it is a common practice for the economic assessment of CO_2-“free” power concepts to specify the additional costs ‘per ton of CO_2 avoidance’ in comparison with a corresponding conventional power plant without CO_2 sequestration. For known economic boundary conditions (i.e. certificate prices), such evaluations can be used to define the breakeven.

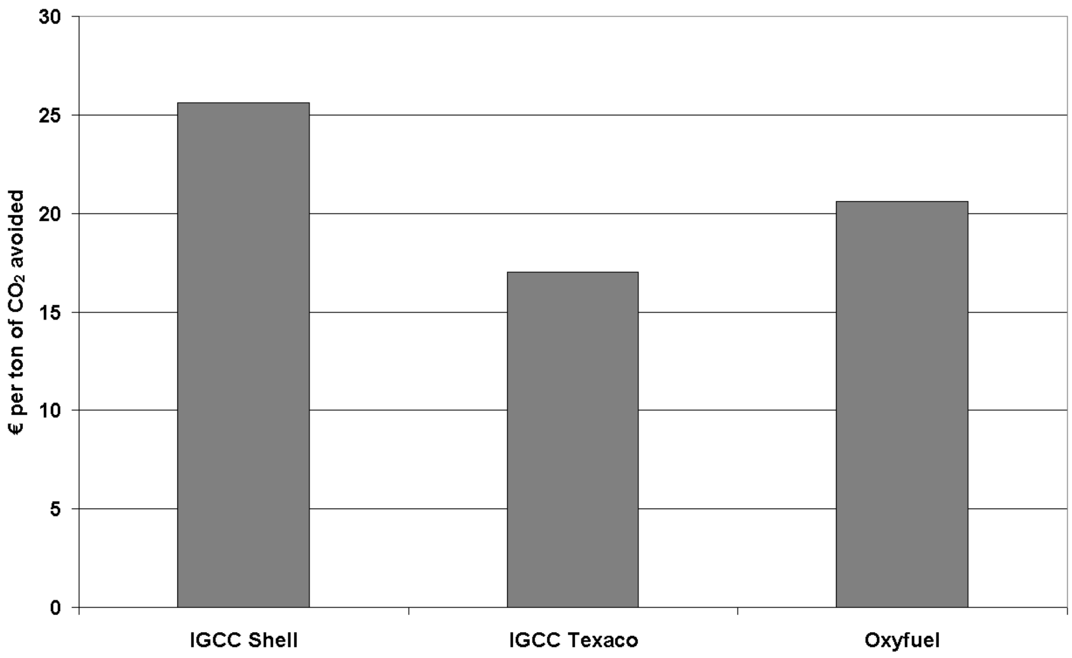


Figure 9: Estimation of CO_2 avoidance costs (Vattenfall AB, 2003)

6. Conclusion

The oxyfuel technology represents a promising option for possible future power generation based on coal but without CO_2 emissions into the atmosphere. The paper has shown that coal-fired power plants with CO_2 separation based on the oxyfuel technology are feasible, assuming a considerable infrastructure for CO_2 transportation and storage.

However, it was also found that decision making for erection of power plants with CO_2 separation will strongly depend on reliable economic boundary conditions for the entire lifetime, which must be provided by policy.

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