

# **IMPROVEMENT OF INTEGRATED GASIFICATION COMBINED CYCLE (IGCC) POWER PLANTS STARTING FROM THE STATE OF THE ART (PUERTOLLANO)**

*Advanced Cycle Technologies*

**Contract JOF3-CT95-0004**

## **SUMMARY REPORT**

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## ABSTRACT



An improved IGCC power plant design was elaborated by the partners of this JOF3-CT95-0004 contract funded in part by the European Commission. The design is based on existing technologies and proven materials, PRENFLO gasifier (Krupp Uhde), cold wet gas cleaning, gas turboset Model V94.3A (Siemens), assuming that this turbine can be operated with coal-derived fuel gas at elevated inlet temperature. Because an IGCC plant based on these components could be built as a follow-up plant of existing IGCC power stations, the new design is termed IGCC 98. According to flow sheet calculations, such a plant would achieve an efficiency of 51.5 % (LHV) and the specific plant costs (plant delivery price) are estimated to amount to 980 ECU/kW (around 1,100 US\$/kW).

An IGCC power plant of this type has outstanding performance characteristics with respect to environmental protection requirements: specific CO<sub>2</sub> emission 0.610 kg/kWh, saleable byproducts like elemental sulphur and slag (building materials), no dry flue ash residues, minimum waste water contaminants, SO<sub>x</sub> and NO<sub>x</sub> emission below statutory limits without secondary measures. Under comparable market conditions, a coal-based IGCC station of this type would be competitive with modern state-of-the-art coal-fired steam power plants (efficiency 45%, LHV).

Considering the increase in fuel gas temperature (as a means to enhance efficiency), autooxidation effects could decrease the heating value and may cause combustion problems. In terms of safety aspects, however, there are no restrictions when using diluent nitrogen with a low O<sub>2</sub> content (below 3 % vol) as is common practice today. This has been experimentally investigated. Moreover, it can be expected that auto-oxidation phenomena will not occur under full scale conditions as a consequence of the turbulent flow regime.

Furthermore, co-gasification of biomass and coal in an IGCC power plant with dry fuel feeding and entrained-flow gasifier (PRENFLO of Krupp Uhde) was assessed. As a result, co-gasification of biomass up to 10% of the total energy input is technically feasible, environmentally acceptable, and even economically profitable, in case low/negative cost of organic waste materials are used, and the biomass-derived power is sold as „Green Power“. The estimates of electricity generation costs are based on Dutch conditions. Application of relatively expensive energy crops, such as willow wood, for this purpose, is also technically feasible and environmentally acceptable, but not profitable from an economic point of view, for the specific Dutch situation.

Techno-economic studies on IGCC plant variants were carried out in order to assess costs (investment as well as electricity generating costs), environmental impact as to enable an insight into the cost structure.

Taking future development into consideration, an IGCC plant based on coal could attain efficiencies up to around 58 % (TIT 1400°C ISO, reheating of gas turbine, optimised humidification, hot gas cleanup, supercritical live steam in the bottoming steam cycle, staged gasification or chemical quench). With a high-temperature fuel cell (SOFC) as a topping cycle, even higher efficiencies are conceivable.



## OBJECTIVES OF THE PROJECT

### Tasks

The aim of this JOULE project is to prepare the design for an IGCC power plant based on components which are commercially available today or are expected to come on the market shortly. For comparison of such a new IGCC power plant with the same site conditions the most advanced conventional steam power plant of the latest design (ELSAM in Denmark) have been selected. The investigations comprise experiments on laboratory scale as well as computations, thermodynamic analyses, design studies and costs estimations. The comparison includes mainly efficiencies, environmental aspects and costs. Therefore, detailed thermo-economic analyses are carried out for costs estimations of IGCC variants. Also the feasibility of co-gasification in an oxygen-blown entrained gasifier originally designed for coal based IGCC power plants was to be assessed and the effect of the biomass co-gasification on the performance, costs and emissions were studied. Furthermore, also the efficiency improvement potentials of the coal-based IGCC power plant which could be exhausted in the long-term are to be investigated.

Preservation of resources, especially considering CO<sub>2</sub> (greenhouse effect), and minimisation of pollution are goals which today determine decisively further development of fossil-fuel-fired power plants. Great efforts are necessary to increase the efficiency of coal-fired power stations. Cost of efficiency enhancement measures does not necessarily induce increasing electricity generating costs. The autonomous market penetration of advanced power plant technologies takes place when fuel savings preponderate the expenditure for the considered improvement measures. The natural-gas-fired combined cycle, for example, does not only achieve a noticeably higher efficiency than the coal-fired steam power plant, but requires even lower capital for investment. Considering the long-term CO<sub>2</sub> emission reduction goals recommended by the Intergovernmental Panel on Climate Change (IPCC), the world-wide implementation of highly efficient coal-fired power plants is absolutely necessary if coal is to remain an important energy carrier in the power sector (today around 40 % of the world's electricity generation is based on coal, 20 % of the CO<sub>2</sub> emission is caused by coal-fired power plants).

According to the contract, the project work is subdivided into four task areas which are strongly interrelated:

- Task 1: Efficiency improvements of IGCC power plants
- Task 2: Increase of gas temperature at the gas turbine combustion chamber inlet
- Task 3: Co-gasification of biomass and coal in an entrained-flow gasifier
- Task 4: Cost optimisation of IGCC stations

Most of the measures for efficiency enhancement influence costs and availability. As any change in design and performance parameters influences the performance of other subsystems, thermodynamic and economy analyses were carried out repeatedly. Therefore, close cooperation of the project partners was imperative.

### **Task 1 Efficiency improvements of IGCC stations**

The IGCC power plant is very likely to profit from some new developments, particularly from the further increase of the gas turbine inlet temperature. Improvements related to process engineering are



also achievable by the efficient use of the sensible raw gas heat and the minimisation of exergy destruction within the gasification process and gas cleaning. A further means to improve the efficiency is to intensify heat recovery by a raw gas / clean gas heat exchanger thus increasing the fuel gas temperature. Other systems to be investigated are e.g. coal preparation, feeding systems and dedusting. The influence of design changes on the plant performance, environmental pollution, plant complexity and costs has to be studied carefully. Energy and exergy analyses and cost assessments have to be carried out for a lot of systems and subsystems.

## **Task 2 Increase of gas temperature at the gas turbine combustion chamber inlet**

The fuel gas temperature is limited by operational considerations of control valves and autooxidation of hydrogen and carbon monoxide. In the most advanced existing IGCC power plant (Puertollano), the fuel gas temperature at the entrance of the combustion chamber is designed to amount to 300°C. At this location, the clean coal-derived fuel gas is mixed with nitrogen from the air separation plant which still contains a certain amount of oxygen. This gives potentially rise to the self-ignition of the fuel gas. Experiments in an existing test rig have been carried out to study the dependence of flammability limits on gas components and other state variables.

## **Task 3 Co-gasification of biomass and coal in an entrained-flow gasifier**

Special problems involved with co-gasification of biomass and coal in entrained-flow gasifiers were investigated. ECN has conducted experiments in an existing laboratory gasifier test rig. The problem areas dealt with concern the behaviour and preparation of fuel, the feeding system and the slag formation. Furthermore, the question of the amount of biomass which can be mixed with different sorts of coal has to be answered. Options of different variants were evaluated by means of techno-economic studies.

## **Task 4 Cost optimisation of IGCC stations**

There are three factors determining electricity generating costs, which can be influenced by design, process engineering and manufacture, namely the investment, fuel consumption and availability. As both the conventional steam power plant, employing supercritical live steam, and the IGCC power plant of previous design (Puertollano type) attain net efficiencies of 45 %, an IGCC successor plant must show better performance and lower electricity generation costs to be competitive. As a consequence, investigations aiming at design improvements had to be carried out in order to accelerate market penetration and to benefit in this way from the environmental advantages of an IGCC power plant in the near future.

Measures for efficiency enhancement very often cause more investment because of the installation of additional equipment and the use of more expensive materials. Such measures are economic as long as the increase of investment costs are balanced by fuel savings.

The influence of improvement measures is analysed in order to reach competitive electricity generating costs. Enhancements of efficiency or reduction of costs must not deteriorate the plant availability. Otherwise, the economy of a power plant would be adversely affected. The proposed design changes will therefore be examined in this respect.



In addition to the investigations of Siemens, Krupp Uhde and University of Essen on the IGCC 98, the Energy Research Centre ECN and University of Ulster, performed economic studies to provide a consistent set of technical, environmental and techno-economic assessment studies covering all of the technologies.

The specific processes that were studied are:

Puertollano plant using local coal and petcoke

Puertollano plant using Pittsburgh No 8 coal

PRENFLO gasifier based IGCC plant using existing technology (base case)

PRENFLO gasifier based IGCC 98.

### ***Background and Role of the Project Partners***

Among the various “clean coal technologies”, the IGCC power plant is characterised by its extremely low environmental pollution and the capability to utilise “dirty fuels” such as coal, oil refinery residues, Orimulsion, waste, etc., and also biomass, if the gasifier is adequately adapted. Moreover, it is to be expected that such power stations will attain higher efficiencies than conventional coal-fired steam power plants even with today’s proven components and materials. This expectation is based on the fact that the natural-gas-fired combined cycle power plant already achieves an efficiency of 58 % at markedly lower investment compared to equivalent pulverised-coal-fired steam power plants, whereby the development potential is still not exhausted. In the case of IGCC stations, coal conversion and gas cleaning cause, of course, some extra losses. The IGCC power plant at Puertollano, Spain, is designed for a net power output of 300 MW and a net efficiency of 45 % (based on so-called standard coal). Today, new conventional steam power plants also attain such net efficiencies and even higher. The potential advantages of IGCC technology are uncontested. However, to demonstrate competitiveness with respect to conventional steam power plants, the efficiency of the IGCC power plant should be increased above 50 % and costs have to be reduced. The IGCC design elaborated in this JOULE Project will be dealt with in the following section as well as the results of investigations of biomass co-gasification and techno-economic studies.

The companies Krupp Uhde and Siemens have manufactured and supplied major components for the Puertollano IGCC power station. Siemens has also delivered the combined gas and steam turbine plant for the Buggenum IGCC power station. They put their knowledge gathered from the engineering of these plants into this project and will furthermore use the design principles and know-how elaborated in this JOULE project for follow-up IGCC power plants.

Co-gasification of biomass in IGCC coal power plants reduces CO<sub>2</sub> emission. The use of this regenerative fuel is a further step towards a sustainable energy supply system. ECN conducts supporting lab-scale experiments and studies different variants of highly and low integrated IGCC systems suitable for co-gasification of biomass and coal.

The University of Ulster carries out detailed techno-economic analyses based on mass and energy balances under the assumption of equal market, ambient and technical boundary conditions. Hence, costs of various power plants and electricity generating costs are calculated without first-of-its-kind costs at the same data base and the results are, therefore, comparable among each other. An important basis for comparison is the techno-economic evaluation of four reference cases which include the IGCC demonstration plant in Puertollano and the starting case of the project with technology of 1996 (base case) and the IGCC 98.



The University of Essen acts as the contract coordinator and contributes to process thermodynamics and optimisation of the IGCC power plants and investigates efficiency improvement potentials and cost effectiveness of improvement measures.

## **SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE PROJECT**

### *The IGCC 98 Power Plant and Further Efficiency Improvement Potentials*

#### **State-of-the-art of IGCC Power Plant and Comparison with Competing Technologies**

##### **State-of-the-art of Integrated Gasification Combined Cycle Plants**

With respect to potential climate change caused by man-made greenhouse gases, especially CO<sub>2</sub>, suppliers of power plants and power plant equipment make every effort to increase the efficiency of future coal-based power stations. At the same time, utilities must take care to decrease electricity generating costs and to come up with a fast return of investment. This is an additional challenge for the power industry since efficiency enhancement generally causes additional investment.

IGCC power plants already built, in operation or under construction and some projects in the planning phase are indicated in Figure 1. The major coal-based IGCC stations already in operation are the European plants Buggenum in the Netherlands (253 MW) and Puertollano in Spain (300 MW, Figure 2) as well as Wabash River (265 MW), Polk County (260 MW) and Piñon Pine (80 MW) in the USA. Several IGCC plants or projects are based on refinery residues. Three of them, currently under construction, are located in Italy (ISAB, SARLUX and API). A growing importance of such plants is expected in the future because IGCC stations are well suited for the environmentally benign utilisation of refinery residues. This enables refineries to increase the production of light distillates from crude oil.

Regarding the design principles and components of an IGCC power plant the Puertollano station is the most advanced IGCC concept with the highest design efficiency for standard coal among the IGCC plants in operation or under construction. Nevertheless, comparing the status of technology in the time of the design of this plant to the present status, some technical progress has been achieved in the meantime, especially concerning the gas turboset.

Starting from the design principles of the Puertollano power plant, an advanced IGCC concept named IGCC 98 has been elaborated in this Joule project. This concept is based on qualified available materials and proven processes. It is characterised by an increase in efficiency and reduced capital requirements compared to previous IGCC plants. The influence of several process parameters and changes in the design were investigated.

In addition, the efficiency potential of future IGCC concepts with more advanced components and process parameters were studied.



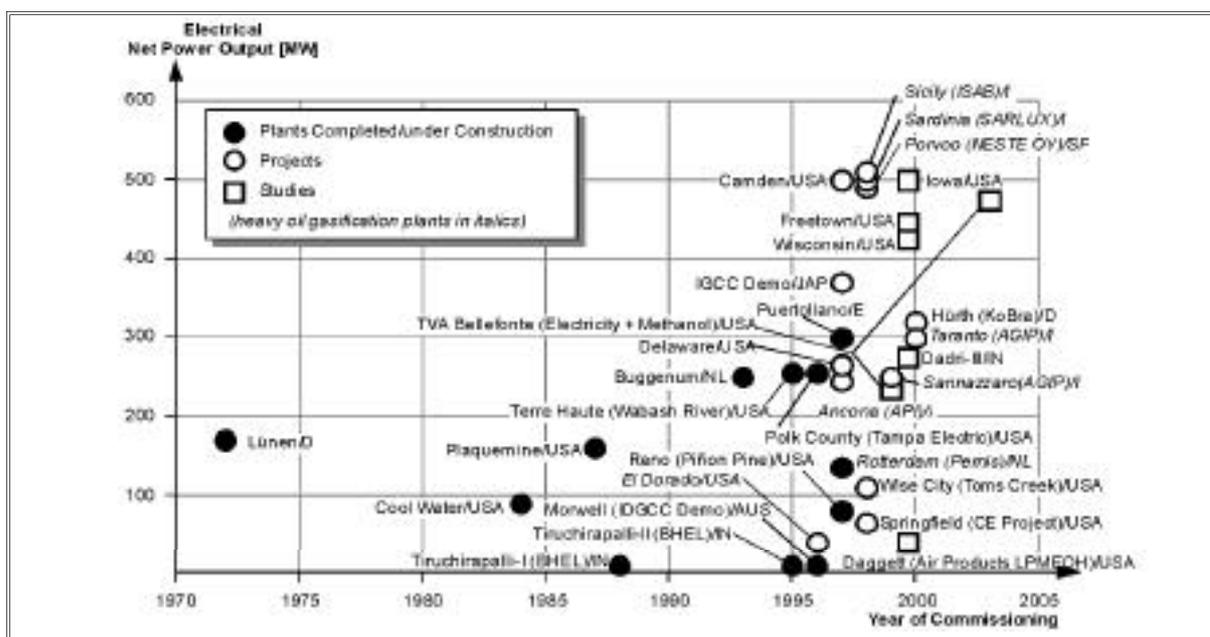


Figure 1 World-wide development of IGCC power plants (selected sites)

### Competing Technologies

Modern conventional steam power plants equipped with pulverised-coal-fired boilers nowadays achieve efficiencies of 45 up to 47 % (depending on cooling conditions). Development programmes aim at even more than 50 %. To attain such high values, ultra supercritical live steam (700°C / 375 bar) must be applied which requires new Ni-based materials. Hence, these prospects have a time horizon beyond the year 2015.

Other trends are directed towards the development of coal-based combined cycles avoiding an air separation plant. In this case, air-blown gasifiers are to be used. Since hard coal can not be completely gasified with air, an additional combustor is necessary to burn the residual char. Studies on such type of power plants, namely the "British Coal Topping Cycle", and extensive tests of an air-blown fluidised bed gasifier and hot gas cleanup have been performed by British Coal and partners. Efficiencies of large scale plants are expected to reach around 50 % (LHV). Similar processes with comparable efficiencies are the second-generation PFBC power plants, e.g. mainly supported by Foster-Wheeler in cooperation with Siemens, and hybrid processes with natural gas topping combustion.

Furthermore, a variety of approaches aim at the elimination of the gasification stage in a coal-fired combined cycle plant. One process route can be characterised as the "Externally-Fired Combined Cycle" (EFCC), employing atmospheric pulverised coal combustion and a heat exchanger which avoids the problem of high-temperature flue gas cleanup. The critical component is the ceramic flue gas/air heat exchanger which is exposed to strong thermal stresses (temperature > 1000°C) as well as mechanical loads (hot / cold side pressure difference 10 to 20 bar depending on the gas turbine) and additionally to corrosive and erosive attacks. Furthermore, the ceramic air heater needs a large surface area and a large volume for a commercial plant which puts questions on the economic prospects.

The mechanical load due to pressure differences across the heat exchanger walls is avoided in the concept of a Pressurised Pulverised coal Combined Cycle using a ceramic Heat Exchanger (PPHECC). In this case, the raw flue gas from the combustor is cooled down by the clean flue gas via a heat exchanger. The raw flue gas is purified by conventional hot gas cleanup (cyclones, filters) and thereafter heated up via countercurrent flow by the impure flue gas.



The most ambitious - but also most straightforward - cycle is the Pressurised Pulverised coal Combined Cycle (PPCC) where hot flue gas from a pressurised slagging coal combustor directly drives the gas turbine without intercooling, only passing a hot gas cleanup between combustor and gas turbine. Such a cleanup system has to handle flue gas, liquid slag and evaporated alkali compounds at around 20 bar total gas pressure and a temperature around 1400°C. Experiments with such a system at pilot scale (1 MW thermal) are ongoing, but commercialisation seems to be beyond the foreseeable horizon.

### Design Improvements and Features of the IGCC 98 Power Plant

The design target is to achieve efficiency improvements of a Puertollano-type IGCC plant based on proven materials and process layout, conventional components, and a Siemens V94.3A gas turbine-generator operated at elevated turbine inlet temperature (TIT). Such a gas turbine-generator is expected to become commercially available in the near future. The North European ambient data as listed in Table 1 have been selected for the sake of comparison with ELSAMPROJEKT’s most advanced coal-fired steam power plant Nordjyllandsværket in Aalborg, Denmark (design efficiency 47% LHV).

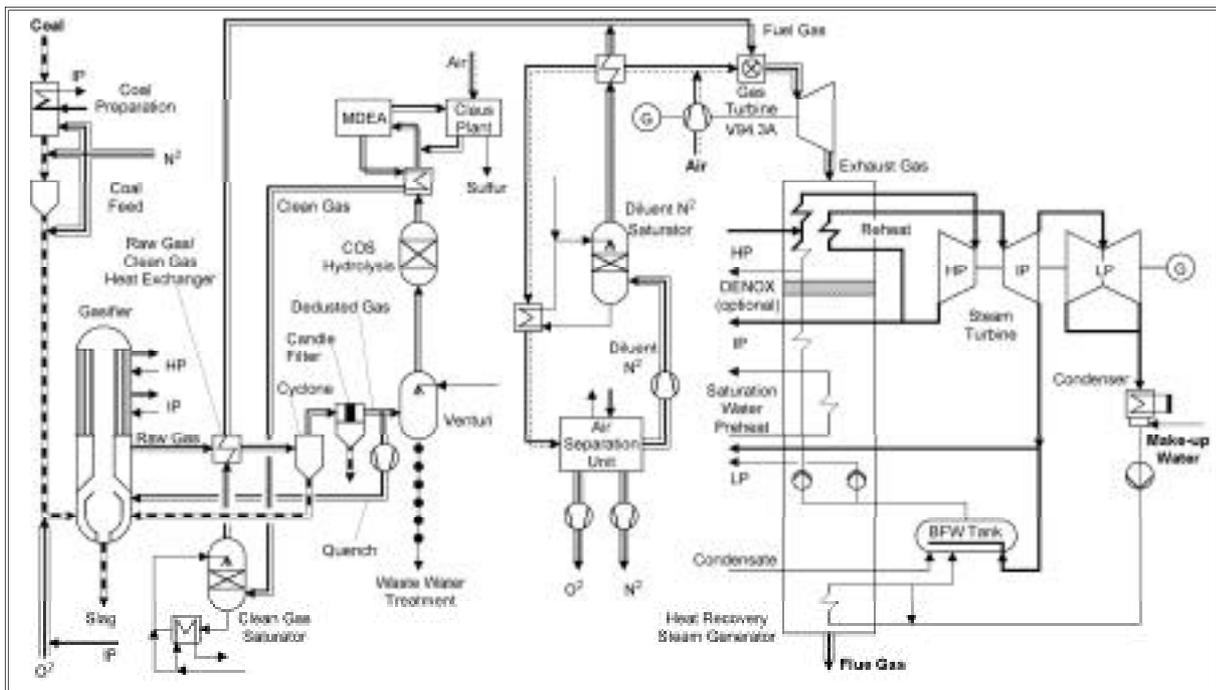


Figure 2 Flowsheet of the IGCC 98 power plant

**Gas turbine:** The IGCC 98 concept is based on an upgraded Siemens V94.3A gas turboset. Although designed for natural gas operation, the highly integrated IGCC concept enables this machine to be operated with coal-derived low-LHV fuel gas.

**Improvement of air separation unit (ASU):** The elevated compressor pressure ratio of the gas turbine of 18 (V94.3A) gives rise to an increased operating pressure of the ASU. The mass flow of diluent N<sub>2</sub> meets the flow conditions at the design point of the gas turbine. As a result of an improved design of the ASU, about 30,000 m<sup>3</sup>STP/h of the waste nitrogen stream can be used internally in an expansion turbine to contribute to the power supply of the refrigeration system. The other part of the waste N<sub>2</sub>



stream is used for inertisation of the coal preparation and feeding system. A nitrogen recovery in the coal drying facility is not necessary.

**Modification of coal drying:** The coal is ground in bowl mills using nitrogen for drying. The drying circuit is heated up to about 250°C by IP-steam and additional burning of a small amount of natural gas. As a result of cost optimisations, no LP steam is consumed for heating. The prepared coal dust has a residual moisture content of about 1.2 % wt and is transported pneumatically under high pressure in dense phase flow with conveying vessels to the coal feed bin. In this way, no coal storage and lock hopper system are necessary and the height of the gasification building can be reduced considerably.

**Layout of the PRENFLO gasifier and heat recovery:** In the PRENFLO gasifier, the coal is converted with O<sub>2</sub> (95 % vol purity) and IP steam to a combustible gas. The gasifier forms an integrated system with the HP convection boiler, installed in one common pressure vessel in which both are linked together functionally and structurally. The gasification chamber works at a pressure of 29 bar and a reaction temperature above the slag melting temperature. Almost 90 % of the ash is removed as slag. Only one slag sluicing line and one slag extractor are necessary for discharging.

Inside the gasification chamber, the fuel is converted to mainly CO and H<sub>2</sub>, the CO<sub>2</sub> content is below 1 % vol. The residence time of the gas is only a few seconds. The raw gas leaves the gasification chamber at a temperature of around 1300°C. At the outlet, the raw gas is quenched by recycled cold clean gas to a temperature of approximately 900°C and thereafter cooled in the convection boiler down to 450°C by producing saturated HP steam at 180 bar. The heat transferred amounts to 7.1 % of the coal energy input (HHV). IP steam is generated by gasification chamber cooling and a smaller portion in the quench pipe.

**Raw gas/clean gas heat exchanger:** Reheating of the clean syngas takes place in the raw gas/clean gas heat exchanger (RCHX). The heat transferred amounts to 2.75 % (HHV) of the coal energy input. High heat flux densities can be achieved in the convection boiler as well as in the RCHX due to the high system pressure on the raw gas side and relatively high mean temperature differences which leads to very compact and economic units. The raw gas, which leaves the convection boiler at a temperature of 450°C, determines the clean gas temperature of 366°C at the hot end of the RCHX and finally the gas turbine fuel gas temperature (mixture of humidified clean gas and humidified diluent N<sub>2</sub>) of 375°C. Commercially available materials can be used for the fuel gas control valves of the gas turbine.

**Dry dust removal:** The dry dedusting system consists of a cyclone separator and a candle filter. Coarse fly ash with a high carbon content removed in the cyclone is recycled to the gasifier and converted to environmentally acceptable slag (Figure 6). Fine fly ash enriched with heavy metals is separated in the candle filter and sluiced out of the system. The quench gas is recycled to the gasifier system with the outlet temperature of the RCHX of about 300°C. The downstream Venturi scrubber is only designed for the removal of water-soluble gaseous contaminants.

Compared with a combined dry/wet dedusting system (Figure 7) consisting of cyclone (coarse dust) and a Venturi scrubber (fine dust), the net plant efficiency is 0.45 % points higher when a dry dedusting system is applied, mainly due to the lower pressure drop in the smaller Venturi scrubber, and reduced losses due to a higher temperature of the recycled gas. The dry dedusting system also has economic advantages compared with the wet dedusting system.



**Fuel gas conditions:** The humidified fuel gas including diluent  $N_2$  and enters the combustion chamber at  $375^\circ\text{C}$ . Due to the low LHV compared with natural gas, a high fuel gas mass flow is necessary for the same total energy supply to the gas turbine. In order to operate at a sufficient margin to the surge limit, the new design of the ASU delivering a reduced diluent  $N_2$  flow fits best to the mass flow ratios and leads to the optimum performance of the machine.

**Measures for reduction of the NO<sub>x</sub> emissions:** To augment the environmental advantage of the IGCC, the concept should aim clearly at reducing NO<sub>x</sub> emissions. The IGCC 98 can meet the legal ordinances by the application of primary measures, i.e., by humidification of both diluent  $N_2$  and clean gas (Figure 8). This results in a water content of 15.3 % wt in the fuel gas before combustion .

Increasing turbine inlet temperatures (TIT) of advanced gas turbines is coupled with higher flame and higher temperatures which cause extensive formation of NO<sub>x</sub>. Regarding the increasingly stringent limits and the gas turbine development, extensive humidification becomes more and more limited, both technically and economically, and may not suffice alone. Furthermore, large amounts of water lost with the flue gas may not be acceptable.

These aspects are arguments for the application of proven DENOX systems. The IGCC 98 power plant, however, can manage without a catalytic DENOX unit. The installation of a DENOX unit in the flue gas path in addition to the primary measures could reduce the NOX emission to the so-called single-digit level. The additional HRSG pressure drop of 5.7 mbar would then reduce the gas turbine power by 0.7 MW and the IGCC efficiency by 0.1 % points.

**Heat recovery from extraction air to ASU:** In a highly integrated IGCC concept, all the air to the ASU is extracted from the gas turbine after the compressor. The heat recovered from the hot air extracted downstream of the gas turbine compressor is first utilised to heat up the saturated diluent  $N_2$  which is routed to the gas turbine combustion chamber, and then to heat up the water for the diluent  $N_2$  saturator. In this manner, most of the energy of the hot air can be utilised very efficiently in the combined cycle process.

**Simplified heat recovery steam generator (HRSG):** A HRSG concept with only one pressure level generating solely HP steam besides feed water preheating and saturator water heating has been selected with regard to cost reduction. There are two reasons why this concept suffers relatively low efficiency losses compared with a dual-pressure or a triple-pressure HRSG: Firstly, the IP steam production in the gas island (gasifier and quench pipe cooling) is nearly offset by steam consumption (coal preparation and gasification) so that the gas island is nearly independent of the power block at the IP pressure level. Secondly, in case of a dual-pressure HRSG, the mass flow through the IP and LP evaporator would be low anyway. On the initial assumption that operation with natural gas is primarily intended only for start-up and shutdown, the IP and LP stage of the HRSG can be omitted. A small remaining demand for IP and LP steam of the gasification island is taken from the exhaust steam of the HP and IP steam turbine.

The make-up water for both saturation systems as well as additional water for saturating the clean gas is preheated to  $175^\circ\text{C}$  in the low temperature section of the HRSG in a separate heat exchanger. The stack outlet temperature of the flue gas leaving the HRSG is adjusted to  $75^\circ\text{C}$ .

This new concept is less complex and reduces the interfaces between gas island and power block further with regard to simplified plant operation.



## IGCC 98 Performance and Environmental Data

*Table 1 Main performance data*

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*Table 5 Environmental impact*

### Influence of Process Parameters

#### Ambient Conditions

Changes of the ambient temperature have an impact mainly on the gas turbine performance and due to a higher condenser pressure also on the steam cycle efficiency. With the assumptions of constant ambient pressure (1.013 bar), a relative air humidity of 80% and a steam cycle condenser pressure which corresponds to the saturation state 12 K above ambient temperature, the net efficiency of the IGCC 98 decreases by around 0.3 % points per 10 K ambient temperature increase. At a higher ambient temperatures the gas turbine and the steam turbine power output are decreased as well as the coal consumption.

#### Fuel Gas Temperature at the Combustion Chamber Inlet

The general intention of preheating the clean gas or the fuel gas, resp. at the gas turbine combustor inlet is to recover heat from the raw gas, thereby reducing the specific coal energy input. Heat recovery could be improved by increasing the surface area of the raw gas/clean gas heat exchanger, which simultaneously gives rise to a reduction of the syngas cooler size. The resulting lower steam production leads to a decrease of the steam turbine power output. On the other hand, the power output of the gas turbine rises on account of the higher fuel gas temperature. Cycle calculations have shown that all effects lead to a modest increase in IGCC net efficiency..



### **Self-ignition of the Fuel Gas**

To assess the maximum tolerable temperature with regard to safety aspects, the self-ignition limits of the fuel gas were investigated, because small amounts of oxygen arising from impurities in the admixed diluent  $N_2$  from ASU with up to 0.6 % vol  $O_2$  are introduced into the fuel gas. In an experimental ignition test rig of Siemens, two different syngases were mixed with  $N_2$  containing 1.1 to 6.5 % vol  $O_2$  at test conditions of 20 bar and up to 500°C. As a result, no safety restrictions were found when  $N_2$  with < 3 % vol  $O_2$  is used. Moreover, the appearance of self-ignition should further decrease in turbulent flow as existing in real combustion chamber inlet facilities. Furthermore, there is some potential to simplify the air separation process due to higher permissible  $O_2$  impurities in the diluent  $N_2$ .

### **Effect of Reduced Fuel Gas Humidification**

The optimal degree of humidification is determined by the available sources of heat at low temperature level which cannot be suitably exploited otherwise. Besides the sensible heat of the extracted air after preheating the diluent nitrogen, the flue gas in the low temperature region of the single-pressure HRSG can be considered in order to achieve a low stack temperature of 75°C. Heat of higher quality such as the heat of evaporation of LP or IP steam is not used.

Applying these principles, further improvement of the IGCC 98 concept could be achieved. The humidification starts at the lowest possible gas temperature. The clean gas is humidified after the desulphurisation at around 20°C and the nitrogen saturator is omitted. The low temperature heat of the coal gas between COS hydrolysis (145°C) and desulphurisation (20°C) can partly be utilised to preheat water from the saturator bottom. The heat of the extraction air is partly taken to produce LP steam. Thus, no LP steam for the gas island has to be extracted from the steam turbines. The remaining heat is taken to heat up water for saturation. These measures result in a higher steam cycle power output.

In this way, the net efficiency of the IGCC 98 power plant can be increased by 0.2 % points up to 51.7 %. As the water content in the fuel gas remains unchanged (15.3 % wt), there is no increase in  $NO_x$  formation and no DENOX unit is necessary.

Regarding the  $H_2O$  level in the fuel gas, it was found that there is an optimum with respect to IGCC efficiency and that this optimum strongly depends on the design of the HRSG, as summarised in Figure 15. Regarding the IGCC with single-pressure HRSG, the optimum water content was found at around 15 % wt, which confirms the design of the IGCC 98. If a dual-pressure HRSG is applied, an improvement of 0.4 % points could be achieved at an optimum water content of about 10 % wt. Selecting a triple-pressure HRSG shifts the optimum  $H_2O$  content to 6 % wt which results in an efficiency advantage of 0.5 % points compared with the IGCC 98 design, i.e. a plant net efficiency of 52% (LHV). In this case, a DENOX unit would be required to meet  $NO_x$  emissions ordinances.

Concerning the specific investment for the IGCC at lower  $H_2O$  contents, the advantages of a smaller gasification island due to lower coal input and a simplified saturation system are counterbalanced by a reduced net electric power output. In order to reduce the electricity generating costs, the higher specific investment for a more complex (dual or triple pressure) HRSG and DENOX unit should not exceed the fuel cost savings. From this point of view, the single pressure HRSG is believed as the more favourable design.

### **Comparison of Natural Gas Optimised with Coal Gas Adapted Gas Turbine**

Compared with a natural gas optimised gas turbine, the main deviations of a coal gas adapted gas turbine in a non-integrated coal gasification power plant are caused by:





Future efforts in cost optimisation could break the barrier of 884  $\text{€}/\text{kW}$  (US\$ 1,000/kW) whereby competitiveness of IGCC could clearly be demonstrated. This can be mainly achieved by increase in unit size and further advances in turbine technology. Also the increase of fuel price (for example by a CO<sub>2</sub> tax) favours the competitiveness of IGCC in relation to PC-fired steam power plants (Figure 20).

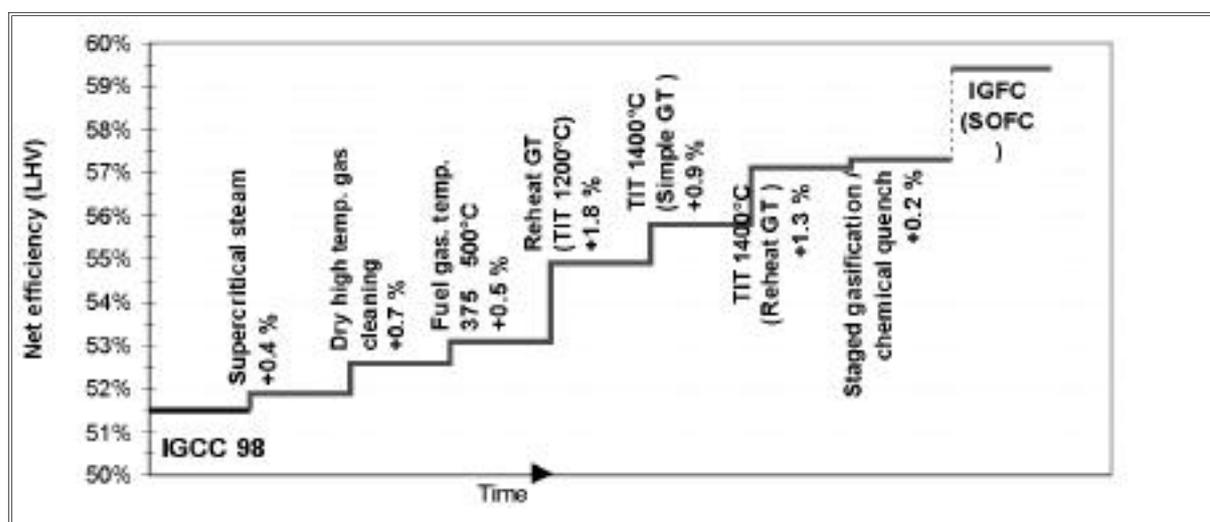
*Table 3 Economic data*

Specific capital (plant delivery price) of IGCC 98	972 $\text{€}/\text{kW}$
Specific capital of PC-fired steam power plant	884 $\text{€}/\text{kW}$
Net plant efficiency of IGCC 98	51.5 %
Net plant efficiency of PC-fired steam power plant	45.0 %
Labour costs	50,000 $\text{€}/\text{man}/\text{yr}$
Maintenance costs	18.5 $\text{€}/\text{kW}/\text{yr}$
Process materials	1.5 $\text{€}/\text{MWh}$
Unit cost of fuel	1.35 $\text{€}/\text{GJ}$
Interest rate	0.08 1/yr
Average nominal escalation rate of investment	0.03 1/yr
Average nominal escalation rate of maintenance costs	0.04 1/yr
Average nominal escalation rate of other costs	0.04 1/yr
Average nominal escalation rate of labour costs	0.04 1/yr
Average nominal escalation rate of fuel costs	0.05 1/yr
Specific staff demand	0.31 man/MW
Utilisation period at maximum load	7,000 h/yr
Average tax rate	0.002 1/yr
Average insurance rate	0.025 1/yr
Payment of the client related to plant cost	0.05% on delivery price
Depreciation period	20 yr
Planning period	1 yr
Construction period	3 yr



## Outlook for Future IGCC Concepts

Starting from the IGCC 98, there are still considerable potentials for further efficiency enhancements, the exploitation of which depends on further development of components. Several of such options were investigated under thermodynamical aspects during the course of this research project by detailed analyses and parameter studies. The highlights are listed below. A plant net efficiency of around 58% should be attainable if the measures listed in Table 4 are applied. Another future (long term) improvement potential could be the use of high temperature fuel cells, such as the solid oxide fuel cell (SOFC) as a topping process. The contributions to the efficiency enhancement by each individual measure are depicted in Figure 4.



**Figure 4** Improvement potential of future IGCC

To simplify the system and to make plant start-up procedures easier, the “non-integrated” concept is often proposed. It should be annotated that for the non-integrated system the gas turboset as developed for natural gas operation cannot be used. Not only modifications of the combustion chamber are required, but also the compressor must be adapted to the flow rates of the non-integrated gas turboset. Furthermore, the attainable efficiency is not higher than in the case of the fully integrated system.

A further variant of advanced coal-based energy conversion systems is the Integrated Gasification Humid Air Turbine cycle (IGHAT). Such a plant dispenses with the bottoming steam turbine. It needs, however, an intercooled compressor, recuperator and saturators. Although not part of this contract, preliminary studies have shown that such a system would probably not attain higher efficiencies than the IGCC power plant but could possibly become less expensive.



**Table 4** *Investigated future options for further enhancement of the IGCC efficiency*

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## *Co-Gasification of Coal and Biomass: „Technical, Economic, Environmental and Experimentally Supported Assessment of Three Concepts“*

### **Introduction**

To accelerate the utilisation of biomass materials for electricity production, in a technically and economically acceptable way, co-firing or co-gasification with fossil fuels, in particular coal, is expected to be the most favourable technology for the next ten years. Further, co-firing or co-gasification, resp. ensures that coal utilisation can be maintained on a sustainable basis, and it improves the environmental acceptability of coal-fired power production. By co-firing or co-gasification with coal, biomass utilisation benefits from the economy of scale, and can potentially be realised at relatively low (additional) investment costs.

The technical feasibility of co-gasification of biomass in oxygen-blown, entrained-flow based, originally purely coal-fired IGCC processes like in Buggenum and Puertollano is still uncertain. Also the effect of biomass co-gasification on the overall net electrical system efficiency of the IGCC process, on the purity of the produced by-products (slag/ash) and on the net power production costs of the total IGCC process is not known. In this project task area these uncertainties are investigated by performing an extensive experimental programme; together with technical, economic, and environmental system assessments.

### **Methodology**

A preliminary study was performed to investigate the technical feasibility of co-gasification of coal and biomass (waste) materials in oxygen-blown entrained-flow based IGCC plants. Experiments were performed to access indistinctness concerning the gasification behaviour of biomass (waste) materials under oxygen-blown entrained-flow gasification conditions, and to fill in lacking input data for the successive system assessments. Technical, economical, and environmental system assessments of a „conventional,, base-case oxygen-blown coal-fired entrained-flow based IGCC process, and of three „advanced,, co-gasification concepts, were performed. The experimental work was performed using biomass/coal research facilities of the Netherlands Energy Research Foundation ECN. The system assessments were performed by ECN, in co-operation with project partners Krupp Uhde GmbH (gasification calculations), Siemens AG (combined-cycle calculations), and the University of Ulster (investment cost data).

### **Preliminary study**

Comparing the required biomass contractability for power production purposes in the Netherlands of 24 PJ in 2000, 45 PJ in 2007, and 75 PJ in 2020, with the current (1997) amount of Dutch contractible organic waste streams available (32.8 PJ), it is concluded that growing of energy crops and/or import of biomass materials is insuperable in the near future (after 2000), to satisfy the required total demand.

It is expected that, in 2020, the contractible organic waste streams will be used together with grown energy crops (willow, hemp, Miscanthus) for small-scale decentral power production, whereas imported biomass probably will be used for co-firing in coal fired power plants (landing stages for ships are already available).



The composition of a variety (more than 1,300) of Dutch biomass materials, both organic waste materials and energy crops, have been enclosed in ECN's data-base „Phyllis. The compositions are reflected in the H/C - O/C ratios, and it is expected that also the conversion characteristics are correlated to these ratios.

## Experimental work

After characterisation of the test fuels (park wood, willow energy crop, and waste wood), ECN's Atmospheric Entrained-Flow Gasification and Combustion (AEFGC) simulator was used for testing the selected fuels under relevant conditions. When woody biomass fuels are fed directly into the gasifier (through separate burners), no problems are expected in relation to conversion efficiency, provided that the fuel used is not too coarse. Particles with a size of 1000 µm may, due to their size and potentially low reactivity, not be gasified fast enough and end up in the wall slag layer; their further conversion then becomes doubtful, and may result in poor biomass gasification efficiency.

Biomass pre-treatment by means of pyrolysis is a method to ensure that the fuel can be pulverised using existing coal mills. In the pyrolysis temperature range of 450-550°C and reaction time range of 5-30 minutes, the grindability of the resulting chars (measured by the Hardgrove Grindability Index) is not sensitive to either temperature or reaction time. As a result of the pulverisation, no problems are foreseen with respect to the level of conversion of pyrolysis chars; this was confirmed experimentally.

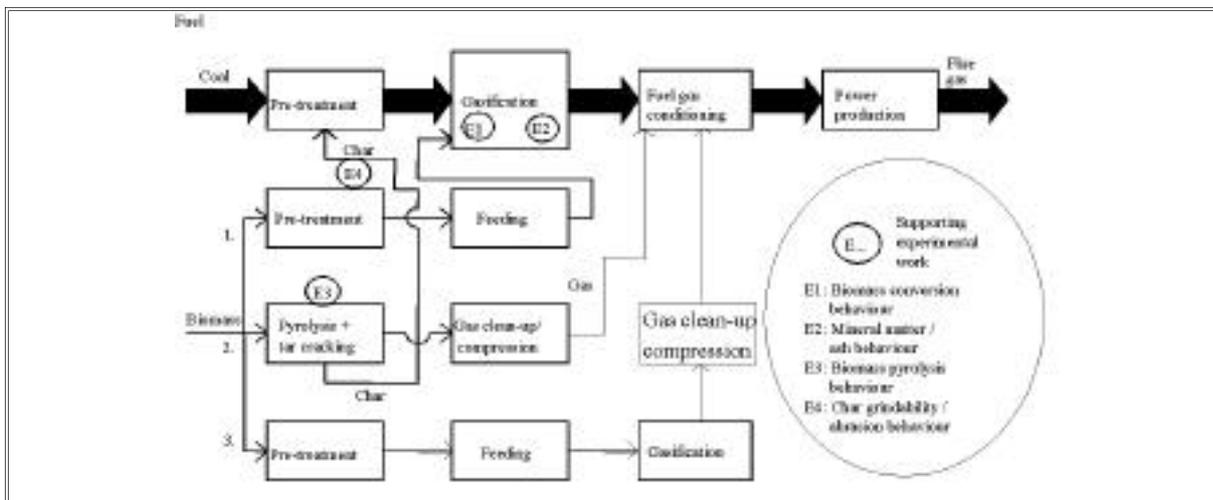


Figure 5 Simplified PFD of advanced IGCC co-gasification concepts.

## System assessments

Three **advanced IGCC concepts** were defined as specifically interesting options for co-gasification of biomass materials in coal-fired oxygen-blown entrained-flow gasification (Figure 5):

- an IGCC concept with separate dry coal and „dry“ biomass feeding systems,
- an IGCC concept with a biomass pre-treatment pyrolysis unit, and a combined dry coal/char feeding system, and
- an IGCC concept based on conventional coal-fired oxygen-blown entrained-flow based gasification



with parallel biomass pre-treatment/gasification, and combined fuel gas clean-up and power production. The IGCC base-case concept of the state of technology of 1996 was taken as starting point for the development of the IGCC 98 power plant and results in an efficiency of 50.1 % (LHV) under Dutch ambient conditions.

Willow wood was chosen as a representative relatively clean biomass material to be used in the system assessment studies. The biomass input for co-gasification was limited to 9.6 % of the total thermal plant input and ensures that the power plant still has to comply with the mild legal power plant constraints. Other important reasons for this constraint and to use only relatively clean biomass materials are that in this way plant committing will not be disturbed to a large extent, and that (mixed) solid waste products will be produced (slag/ash) that still could be sold on the commercial market. The total thermal plant input (about 89 MWth LHV) corresponds more or less the maximum amount that is contractable of a genre organic waste streams in the Netherlands.

### **Co-gasification concept 1:**

In this concept, the wood is pre-treated in a combined drying and size reduction unit, as applied already in the Dutch Gelderland Power Plant 5. The moisture content of the willow wood is reduced from 50 % wt a.r. to 8 % wt by indirect drying with pre-heated air (heated by the flue gas produced in the HRSG). The wood powder is fed separately to the pressurised gasifier through an advanced feeding system, and pressurised by process nitrogen, produced as by-product of the Air Separation Unit (ASU) of the integrated IGCC process. An internal power consumption for the total pre-treatment section of 120 kWhe/ton raw biomass material has been assumed (size reduction: 100 kWhe/ton, transportation/feeding: 20 kWhe/ton).

### **Co-gasification concept 2:**

In this concept, dried willow wood is pre-treated in an atmospheric pyrolysis unit. The wood is dried from 50 to 15 % wt moisture in a rotary drum dryer, using the flue gas from the HRSG of the IGCC plant as drying medium. The char produced in the pyrolysis is fed into the gasifier through the conventional coal feeding system. The tars available in the raw pyrolysis gas are cracked in a separate tar cracker. Downstream of the cracker, the pyrolysis gas is quenched, cooled, and cleaned in a „wet“ scrubber. The endothermic pyrolysis process is driven by burning part of the produced pyrolysis gas; the other part is compressed to IGCC plant conditions in a multi-stage compressor. This part is mixed with the char/coal-derived fuel gas, just downstream of the cyclone separator, in the fuel gas conditioning section of the IGCC plant. Both the heat produced by cooling the raw pyrolysis gas and that of cooling the pyrolysis-derived flue gas are utilised in the HRSG of the IGCC plant. The results of the experimental work, concerning the amount and composition of char, pyrolysis gas (and pyrolysis-derived flue gas), are used to develop a computer model, resulting in an overall efficiency of 71.4 % HHV of the pyrolysis pre-treatment process.

### **Co-gasification concept 3:**

In this concept, the willow wood is gasified separately in a combined air-blown atmospheric CFB gasifier (900°C)/air-blown atmospheric CFB tar cracker (920°C). The wood is reduced in size in a conventional shredder and dried to 10 % wt moisture in a rotary drum dryer, using part of the energy



available in the flue gas from the HRSG of the IGCC plant. After gasification, the produced biomass-derived fuel gas is cooled, producing an amount of superheated steam for additional power production in the combined-cycle of the IGCC plant, scrubbed, compressed in a multi-stage biomass-derived fuel gas compressor, and mixed with the coal-derived fuel gas, just downstream of the cyclone separator.

The results of the integral system calculations can be further optimised in favour of the biomass co-gasification options by:

modifying the input data, and optimising the models, especially to co-gasification conditions;

application of more efficient modified pyrolysis pre-treatment process (minimising pyrolysis gas production/maximising char production or pressurised pyrolysis), resulting in an increased total gross electrical plant output;

application of a pressurised gasification pre-treatment process, resulting in a decreased total internal power consumption.

Co-gasification of biomass (willow) in an adapted PRENFLO-based IGCC plant, results in a net electrical efficiency of about 1.4 to 2.1% points (LHV) below that of the reference IGCC plant without biomass co-gasification. With an adapted and optimised PRENFLO-based IGCC plant, the net electrical efficiency is 0.5 to 0.1 % points lower than that of the reference IGCC plant without biomass co-gasification.

The net electrical efficiency for conversion of the biomass part alone amounts to 28.4 to 35.8 % LHV (27.4 to 34.4 % HHV) or 45.1 to 49.3 % LHV (43.4 to 47.5 % HHV) in case of the optimised co-gasification. For comparison: the efficiency of a stand-alone air-blown Biomass IGCC (BIG/CC) system with the same capacity is 40 % LHV.

The different co-gasification concepts were compared with regard to the economic profitability of the additional investment for co-gasification, by means of the Simple Pay Back Period (SPBP)<sup>6</sup>, the Net Present Worth (NPW)<sup>7</sup> and the Internal Rate of Return (IRR)<sup>8</sup>. Furthermore, the CO<sub>2</sub> avoidance costs are given. In contrast to relatively expensive energy crops (willow wood), co-gasification of organic waste materials such as waste wood, park wood (in the Netherlands), especially in the optimised co-gasification concepts, is judged to be very promising from an economic point of view.

## *Cost Analysis and Environmental Impact*

In addition to the investigations of Siemens, Krupp Uhde and University of Essen on the IGCC 98, the Energy Research Centre performed thermo-economic studies to provide a consistent set of technical, environmental and economic assessment studies covering all of the technologies.

Within this project, the specific objectives were:

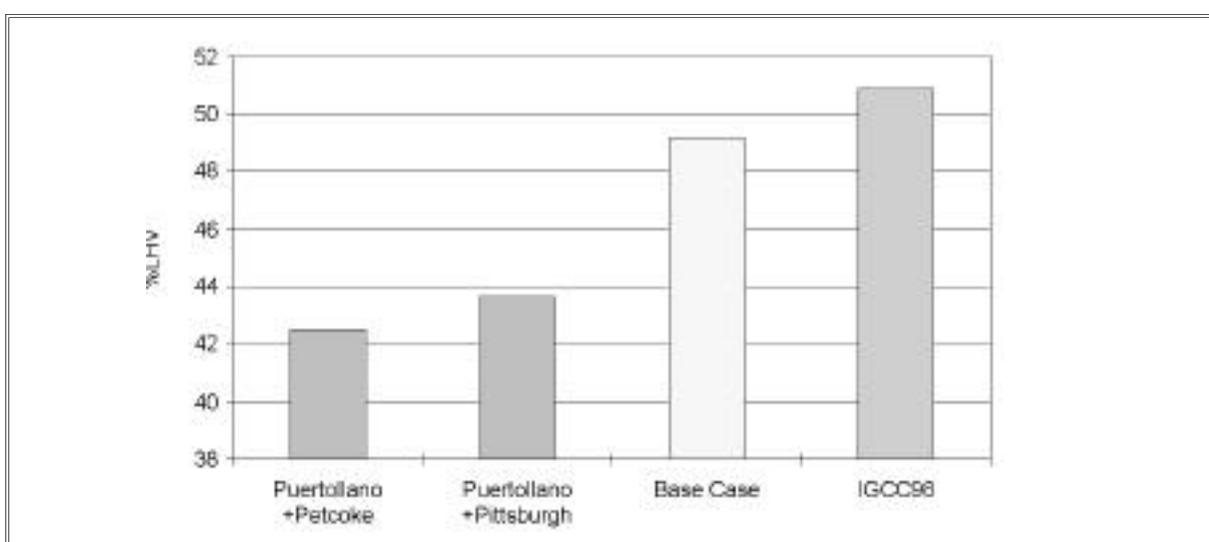
- to evaluate the existing IGCC plant which has been constructed at Puertollano when firing the local coal / petcoke mixture
- to compare this with the performance when using a standard internationally recognised coal such as Pittsburgh No. 8.
- to provide an assessment of the IGCC 98 concept.
- to assess the sensitivity of the analysis to variations in the plant performance.



The specific processes that were studied are:

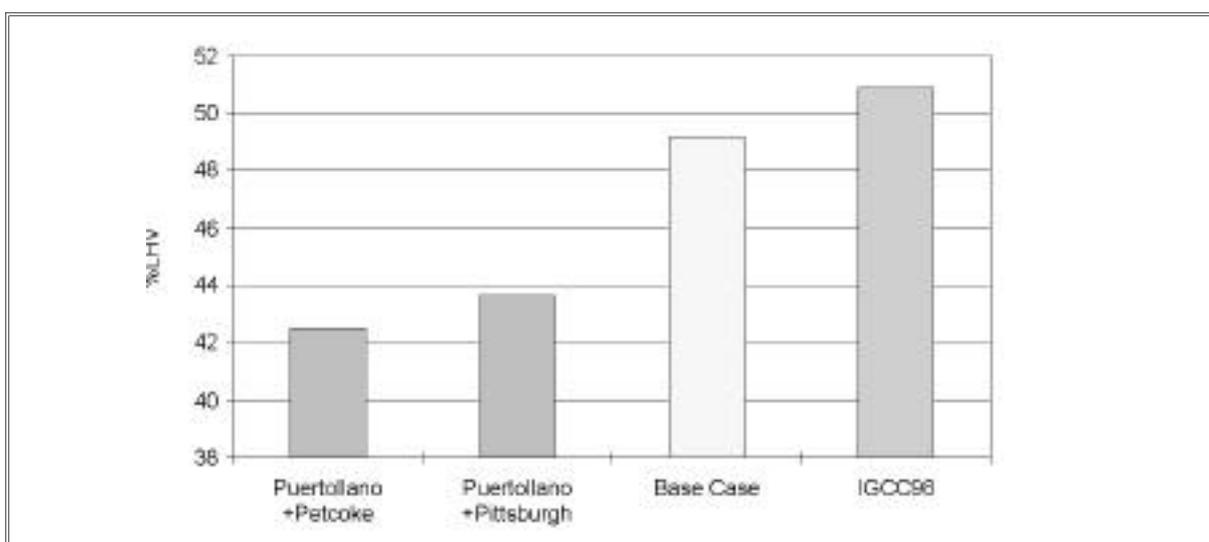
- the Puertollano plant using local Spanish coal and petcoke
- the Puertollano plant using Pittsburgh No 8 coal
- the PRENFLO gasifier based IGCC using existing technology
- the PRENFLO gasifier based IGCC using the IGCC 98 concept.

The efficiency results (Figure 6) show good agreement with the values of the partners, although there is a small reduction in output from the steam turbines and an increase in auxiliary power requirements. There is a significant reduction in CO<sub>2</sub> emissions (Figure 7) in part due to the change of feedstock and in part to the efficiency improvement.



**Figure 6**

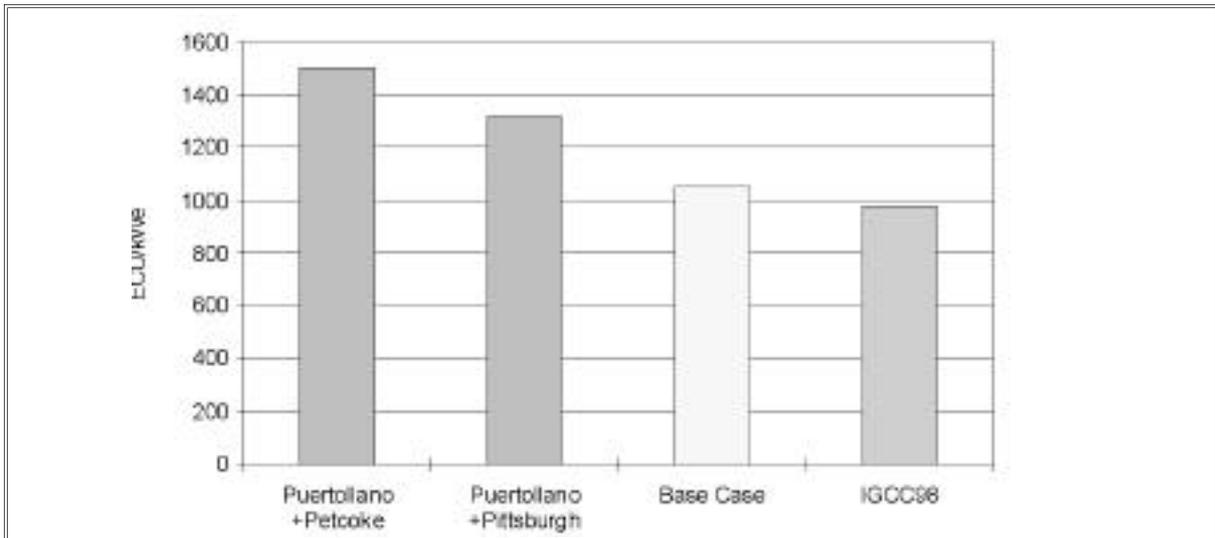
**Efficiency of systems**



**Figure 7**

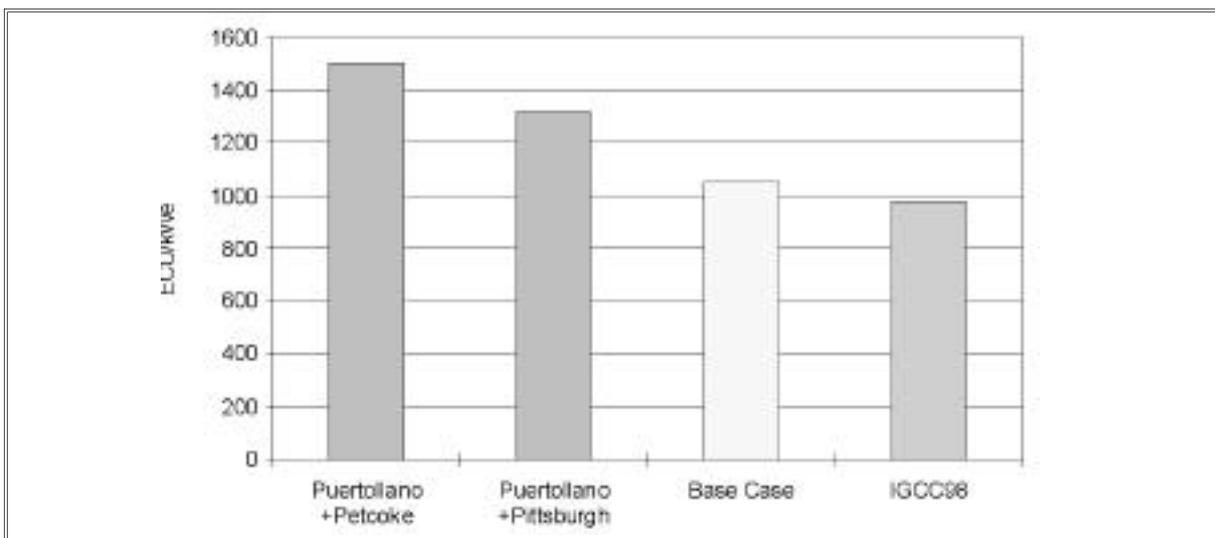
**CO<sub>2</sub> Emissions**





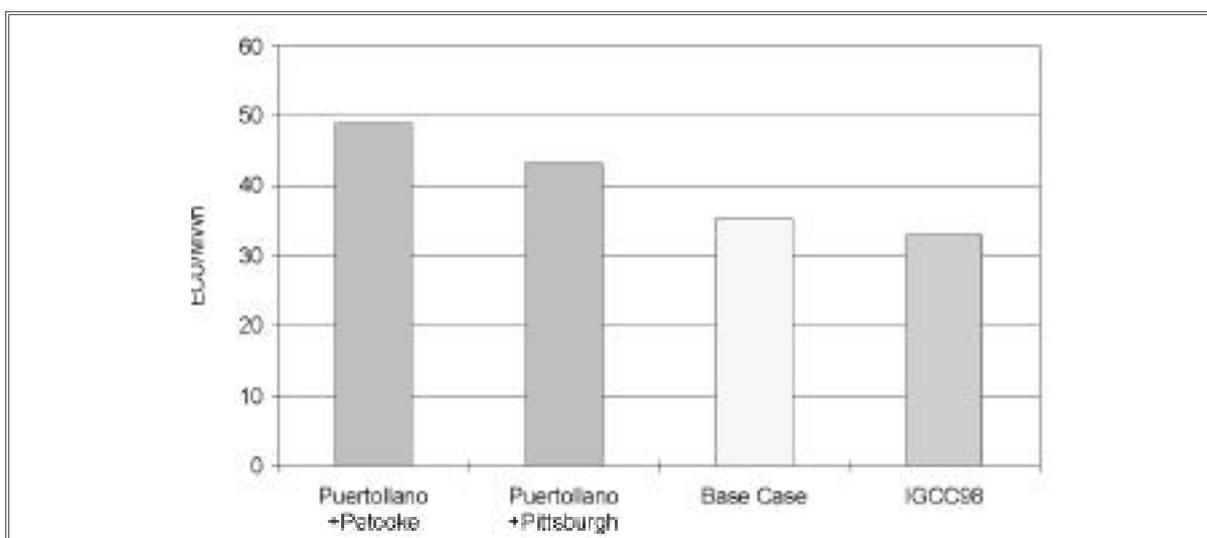
**Table 9** *Process Design Conditions*

If the Puertollano plant had been designed specifically for Pittsburgh No 8 coal, the specific investment (Figure 8) would have been reduced from 1,500 ECU/kWe to 1,310 ECU/kWe. These costs are substantially lower than the actual costs of building Puertollano because they do not include the extraordinary costs associated with building the first plant of this type. The IGCC 98 concept was estimated at a specific investment of 980 ECU/kWe. This is somewhat higher than the estimates of the IGCC 98 plant by Siemens/Krupp Uhde/University of Essen, in part due to the slightly lower efficiency, and in part due to the fact that the coal reception, storage costs and ash handling costs were included in the estimate. For the IGCC 98 concept, a levelised cost of electricity of 33 ECU/MWh was calculated based on a fuel price of 1.24 ECU/GJ, 7.5% DCFR, 85% occupancy and 25 year plant life time (Figure 9).



**Figure 8** *Specific investment*





**Figure 9** *Electricity cost*

A series of sensitivity analyses were performed to assess the effect of varying certain parameters on the cost of electricity for the IGCC 98 process. These parameters include fuel price, discounted cash flow rate, plant life and occupancy.

Compared with the Puertollano plant using Pittsburgh No 8 coal, the IGCC 98 process has an improved efficiency of 7.3 % points, a reduction in CO<sub>2</sub> emissions of 92 g/kWh, a reduction in specific investment of 340 ECU/kWe and a reduced electricity cost of 11.4 ECU/MWh. To reduce the electricity cost by 1 ECU/MWh requires an efficiency improvement of 3 % (constant capital cost), reduced fuel price of 0.14 ECU/GJ or a reduction in capital investment of 4 % (constant efficiency).

## CONCLUSIONS

Regarding efficiency, modern pulverised coal-fired steam power plants are nowadays entirely comparable with the most advanced existing coal-based IGCC plant (Puertollano). Hence, efficiency improvement and cost reduction are necessary to promote the market penetration of the environmentally benign IGCC station as a viable power generating system. To show what is feasible today, a variety of design and process studies were carried out.

The design of the **IGCC 98** is based on proven materials, components and processes. With the gas turbine generator Model V94.3A operating at elevated turbine inlet temperature as expected to be commercially available in the near future, the net plant efficiency is calculated to amount to 51.5 % (LHV; up to 51.7 % with optimised humidification) and the specific plant cost (delivery price without owners costs) to 972 €/kW (US\$ 1,100/kW). Under the present market conditions, the IGCC 98 power plant is competitive compared with a modern PC steam power plant (45 % efficiency). The efficiency could be somewhat increased, if a triple pressure HRSG would be installed. A comprehensive study on “**future IGCC**” concepts reveals further efficiency improvement potentials resulting in IGCC plant efficiencies up to around 58 %. With a fuel cell system (SOFC) as topping process, even higher efficiencies are conceivable.



The **co-gasification** of biomass and coal in an IGCC plant is a further prospect to reduce CO<sub>2</sub> emission and to preserve non-regenerative fuels. From gasification experiments and computer-modelling of a co-gasification IGCC station with the limitation of the share of biomass to about 10% of the total energy input, it was concluded that co-gasification of biomass and coal in an oxygen-blown entrained-flow based IGCC plant is technically feasible.

The net electrical plant efficiencies of all co-gasification concepts are lower than that of the IGCC plant fired with coal only. This lower efficiency is mainly due to the high internal energy consumption for biomass pre-treatment and process compressors. This decrease in net electrical plant efficiency can be reduced by further optimisation and integration, and by pressurisation of the pyrolysis/gasification biomass pre-treatment processes. With these modifications, it is expected that the decrease in net electrical plant efficiency, due to co-gasification, can be limited to maximally 0.5 % points (LHV).

The economic aspects were studied for the specific situation in the Netherlands. In contrast to relatively expensive energy crops (willow wood), co-gasification of organic waste materials such as waste or park wood is judged to be very promising from an economic point of view, especially in the optimised co-gasification concepts.

A **thermo-economic** comparison of the IGCC 98 with the Puertollano plant based on the same coal (Pittsburgh No. 8) demonstrated an efficiency improvement of 7.3 % points and a CO<sub>2</sub> emissions reduction of 92 g/kWh. Resulting from lower specific investment of 340 ECU/kW, the electricity generating costs decrease down to 11.4 ECU/MWh. To reduce the electricity costs by 1 ECU/MWh requires either an improvement of efficiency of 3 % points (assuming constant capital cost) or a fuel price reduction of 0.14 ECU/GJ. For constant efficiency, the capital investment must be lowered by 4%.

