The “CombiPower Process” – a Possibility for Decentralized Generation of Power, Heat and Industrial Gas from Coal and Biomass*)

Von Dipl.-Ing. Norbert Topf, Dipl.-Ing. Madeleine Berger, Dipl.-Ing. Gert Palitzsch und Dr.-Ing. Sascha Schröder, Dresden

Summary A process (the CombiPower process) is presented that combines fluidized bed gasication with air as the gasification medium and fluidized bed combustion. With this process, decentralized generation of electric energy and heat from biomass in compliance with the regulations of Germany’s Renewable Energy Act (EEG) is feasible both with regard to the processing equipment required and in terms of economic efficiency. By enriching the oxygen content in the air, e.g. to around 50 % O2, in the CombiPower-Plus process, an industrial gas with a caloric value of around 8 MJ/kg can be produced. Moreover, compared to an otherwise identical CombiPower plant, the fuel rating can be increased by a factor of 2.5 to 3. Feasibility studies show that with a further global increase in the prices for energy resources, besides the use of regenerative raw materials such as wood, regionally available brown coal can also be used cost-efficently for decentralized energy conversion.

1. Introduction

Climatic change, the scarity of fossil fuels, the steady rise in their price, and the increasing pollution of the air by emissions – these are all things are forcing people to think again about the way we use and manage the resources of our earth. In this context, not only the increased use of alternative energies such as wind, solar energy, biomass or geothermal energy is attracting more and more interest, but the respective potential of an energy resource, its availability and its scope are also evaluated.

“Crude oil“ is the key currency on the world fuel market [1]. Today, oil is equally an economically and politically important factor. The development of the price of crude oil over the last three level of almost 80 US $/barrel (Fig. 1). Contrary to widespread opinion, this price increase cannot, however, only be explained faster growing global economy and rising energy demand.

In China alone, around 20 mill. cars were produced and licensed for the first time over the last 3.5 years. This corresponds to around half of the total vehicles in the Federal Republic of Germany and serves as a rough guide for forecasting the future energy requirement in this up-and-coming economic region alone.

Consequence of the drastically increasing global demand for oil dustry It is therefore important to develop and realize new ideas for regional, efficient energy generation on the basis of indigenous resources.

Especially the indigenous coal Reserves and the potential for the material and technical development of regenerative energy sources can open up numerous avenues for lowering dependence on energy imports in the long term and the build-up of a value added chain.

The CombiPower process presents an interesting possibility for the efficient generation of “clean” energy on the basis of domestic resources in a future-oriented system. The objective of this paper is to present a technical description of the process and plant engineering and, in addition, to establish the applicability of the CombiPower process based on feasibility studies.

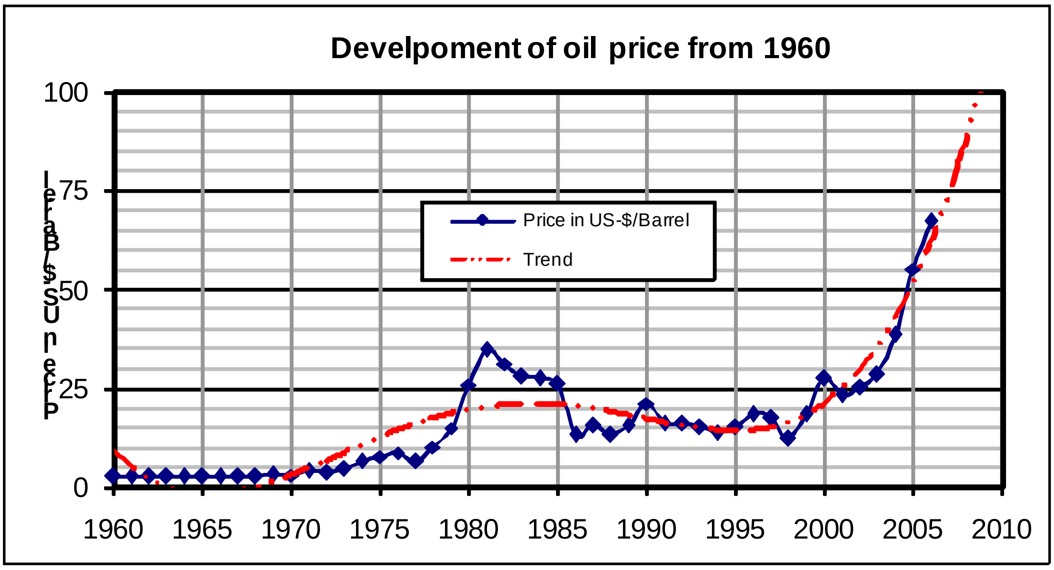

Fig. 1: Development oft he oil price from 1960 to 2006

2. Process Description

The CombiPower process is used for the decentralized generation of power and heat from solid fuels such as biomass, brown coal commercial waste-derived fuels (WDF) from processed domestic waste or commercial waste with air as the gasification medium.

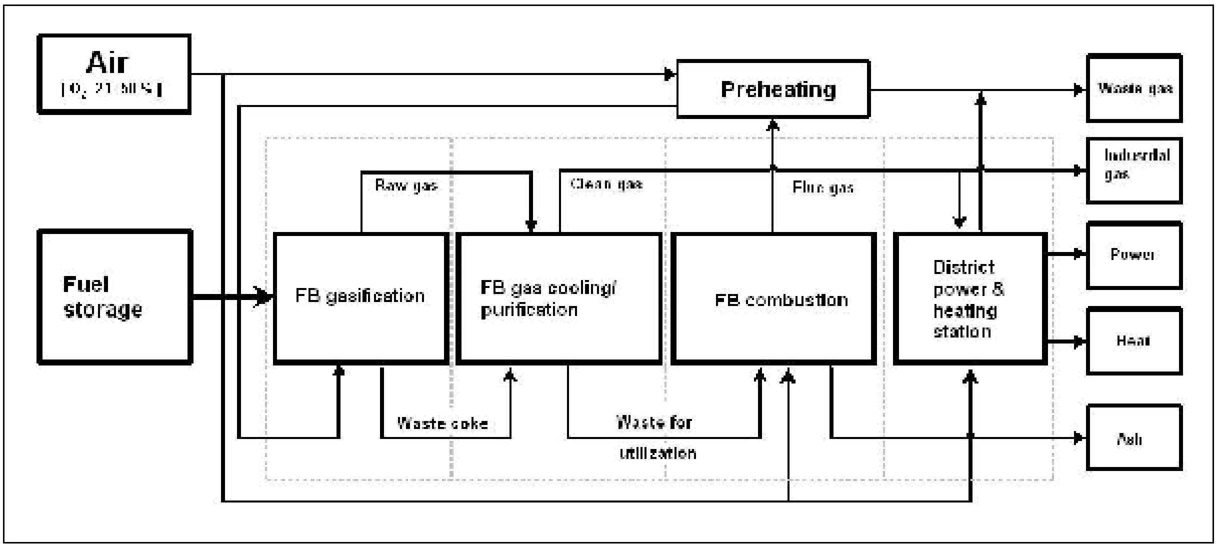

Fig. 2: Flowsheet of the CombiPower-Plus process, schematic

Fig. 2 shows a flowsheet of the CombiPower process with the main process stages

- fluidized bed gasification
- gas cooling and purification in the fluidized bed
- fluidized bed combustion
- biomass, WDF or brown coal district heating and power station.

On the basis of this concept, the CombiPower-Plus process also offers the possibility of producing industrial gas in addition to the generation of power and heat based on the use of oxygen-enriched air as the gasification medium.

For this purpose the existing plant is simply extended with oxygen enrichment in a pressure swing adsorption plant.
At a throughput of m_{BS} = 3.5 t/h fuel, specific useful energy in the form of electric energy (power – P_{elt} = 1.5 MW/h), thermal energy (heat – Q_{therm} = 2 MW/h), and industrial gas (Q_{chem} = 8 MW/h) can be produced.

2.1 Plant Engineering

The three-stage fluidized bed plant (FB plant, Fig. 3) with the above process stages consists of the following subsystems

- fuel storage with testing system determining the fuel quality
- gasifier with feed system
- fuel gas processing (purification and cooling)
- combustion chamber with ash discharge
- ash storage
- district power and heating station
- emergency are stack
- recooling unit
- oxygen enrichment.

These subsystems are briefly described below.

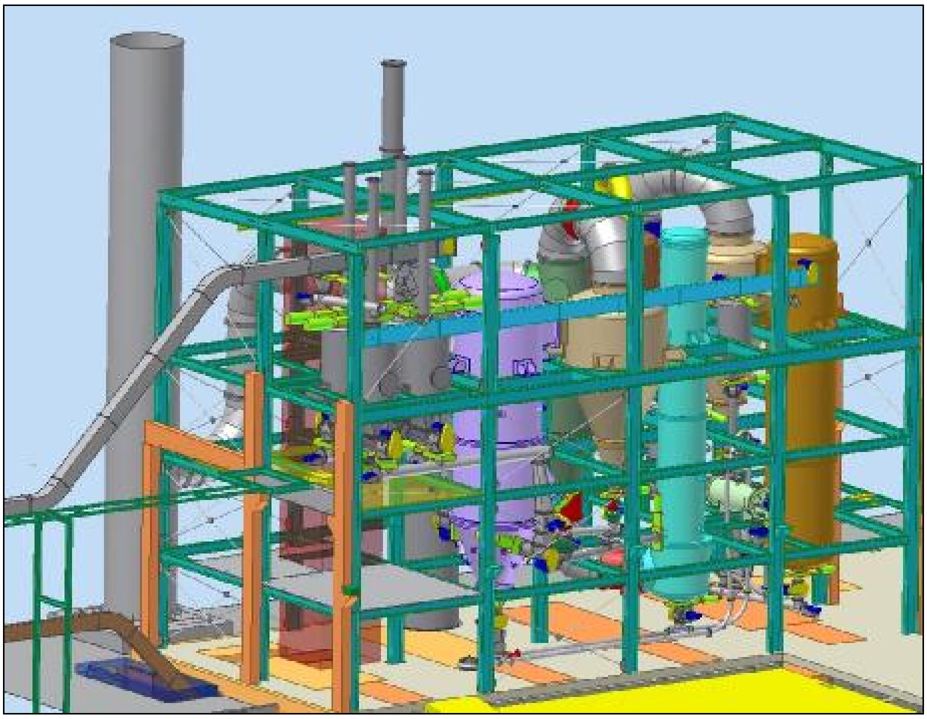

Fig. 3: View of the three-stage fluidized bed system of the CombiPower process

2.1.1 Fuel storage and fuel quality

The precondition for continuous operation with consistent fuel quality is storage of the fuel for at least six months. The fuel is pre-dried utilizing waste heat from the overall process.
The fuel must have a particle size distribution suitable for treatment in the fluidized bed, and the conveying and metering systems must be adapted appropriately. In the plant currently in planning only untreated wood in the form of chippings in the particle size range from 0 to 20

mm will be used. The preferred feed is a material with a water content < 18 wt. %, but water contents up to 30 wt. % are possible. The caloric value H_u should not fall much below 12 MJ/kg. The fuel should be free of metallic and other impurities.

The fuel is metered and fed by means of pusher plates and troughed chain conveyors.

Table 1: Fuel characterization

Input material	Wood chippings	Dry brown coal
Particel size range	0-20 mm	0-6 mm
Caloric value [MJ/kg]	14.860	21.650
Water content [wt.%]	18	9.9

2.1.2 Gasifier

Core element of the entire plant is the fluidized bed gasifier in which the fuel is converted with a substoichiometric quantity of air into a combustible gas mix (fuel gas) with the main components CO, CO_2, CH_4, H_2, N_2 and water vapour.

Gasification is performed in a stationary operated fluidized bed with coke as the fluidized bed material and preheated air as the fluidized medium at around 620°C. The gasifier is operated with slight overpressure to compensate for the pressure loss in the subsequent gas purification stage.

The fuel is fed into the fluidized bed by screw conveyors above the gasifier nozzle plate. A system of screw conveyors and a gas-tight-sealed double gate reliably prevents reburning.

2.1.3 Fuel gas processing

The fuel gas is first dedusted in a hot gas cyclone. This is followed by cooling from around 620°C to around 100°C in a downstream fuel gas cooler, which is also designed as a stationary fluidized bed with indirect water cooling (cooling dampers). The waste coke from the fluidized bed gasifier is used as the fluidized bed material. Here the crude gas is first quenched and then indirectly cooled. The tar contained in the gas condenses on the fluidized bed material. The tar-loaded spent coke is transported by a screw conveyor to the downstream combustion stage and burned off there. With this process, a continuous renewal of the bed material in the FB cooler and a complete energy conversion of the carbon including the tar are ensured.

Cooling of the crude gas is followed by further cleaning of the fuel gas with scrubbers, mist collectors, reheating, activated carbon adsorption and, if required, removal of the fines. The heat emitted by the fuel gas in the FB cooler is used to heat hot water.

2.1.4 Combustion with ash discharge

The waste materials including the surplus water accumulated during gas production and purification are evaporated or burnt off in a third stationary fluidized bed at temperatures of around 900°C. The energy of the flue gas is used to preheat the air for gasification. The flue gases comply with the requirements of Germany’s Clean Air Act, the suitability of the ash for landfilling is guaranteed. This is discharged via a cooled star wheel and a screw conveyor and stored in a collecting tank.

2.1.5 Combined power and heat generating plant with emergency flare stack

The cleaned fuel gas passes a gas mixing control system, a turbocharger and a compound cooler. The working machine consists of a four-stroke gas Otto engine, which drives a three-phase synchronous generator. The flue gas is fed through a regenerative thermal reactor in which the remaining CO is converted at around 800°C. The flue gas cooling is used for the production of hot water. An emergency flare stack is used for the safe combustion of the fuel gas during non-steady operation of the gasifier and fuel gas processing (start-up and shutdown, faults).

2.1.6 Recooler

The cooling water from fuel gas purification (scrubber) and the district power and heating station (motor cooling) is recooled in a drying and cooling tower with forced ventilation. The warm exhaust air from this process is used for pre-drying of the fuel.

2.2 Process parameters

The process was balanced and calculations based on variation of the input and output values were performed with the “Palito” program developed by VER GmbH [4]. The oxygen content in the gasification medium and the mass flow of the fuel were varied.

2.2.1 Input and process data

Besides waste wood from forestry and plantations other bio-masses such as straw, miscanthus, whole plants are possible feed materials. Brown coal is another regionally available feed material. Even the use of fuel derived from processed waste (WDF) is generally possible in this system.

The following process balance of the CombiPower plant is based on the example of untreated wood (fuel 1) and dry brown coal (DBC, fuel 2) (characterization in Table 1). With an O_2 content of 50 % in the gasification air, the fuel throughput can be increased by a factor of 2.2 for wood and 2.8 for dry brown coal with the same plant configuration (Table 2). Furthermore, with such a process, the specific investment can be lowered from around 3,750 t/kW$_{elt}$ to below 2,000 t/kW$_{elt}$.

Table 2: Process input data

Fuel	**Without oxygen enrichment**			**With oxygen enrichment (O_2 = 50 %)**		
	Quantity of fuel [kg/h]	Gasification air [m^3 $_{i.N.}$/h]	Combustion air [m^3 $_{i.N.}$/h]	Quantity of fuel [kg/h]	Gasification air [m^3 $_{i.N.}$/h]	Combustion air [m^3 $_{i.N.}$/h]
Wood (F 1)	1289	1537	472	3500	1666	493
Coal (F2)	849	1466	607	2400	1031	742

2.2.2 Output

Table 3 shows the output data for the two fuels with an energy production of P_{elt} = 1.5 MW and production of industrial gas. If with the same input, no industry gas is produced, it is possible to increase the conversion rate into electric energy: wood to P_{elt} = 4.3 MW; coal to P_{elt} = 4.5 MW. It should be noted that a corresponding number of additional district power and heating stations must be installed (capacity expansion) (Table 4).

Besides the increase in the generation of electric energy, the amount of heat released also increases from Q_{therm} = 2.0 MW to 2.7 MW (wood) and 3.1 MW (coal).

Table 3: Process output data

		Power		Heat		Industrial gas			Flue gas		Ash	
	Unit	F1	F2	F1	F2	F1	F2		F1	F2	F1	F2
Capacity:	MW	1.5		2		8	8.5		0.9	0.4		
Volume flow:	$m^3_{i.N.}$ /h					3600	3300		6730	5835		
Mass flow:	kg/h					3500	3100		8760	7795	17	120
Temperature:	°C					39	40		85	58	900	900
Composition:	Vol.% (CO_2)					17.1	1.6		15.4	15.5		
	Vol.% (H_2O)					4.3	4.3		17.4	9.5		
	Vol.% (N_2)					15.1	17.2		62.4	68.5		
	Vol.% (O_2)								4.8	6.5		
	Vol.% (H_2)					33	26.3					
	Vol.% (CO)					28.4	50.4					
	Vol.%(CH_4)					2.1	0.2					
Caloric value:	kJ/kg					8200	9900					

Table 4: Electric energy supply at constant industrial gas production of Q_{chem} = 4MW

O_2 content [%]	Pelt (F1) [kW]	Pelt (F2) [kW]	No. district power and heating station
30	998	1091	1
50	2880	3062	2
70	4647	4864	3
90	6401	6739	4

2.3 Process parameter variations

The oxygen content in the range between 21 and 100 % is regarded as a process variable. On commercial scale, an O_2 content up to 95 % (5 % N2) can be cost-efficiently produced with the pressure swing adsorption process.

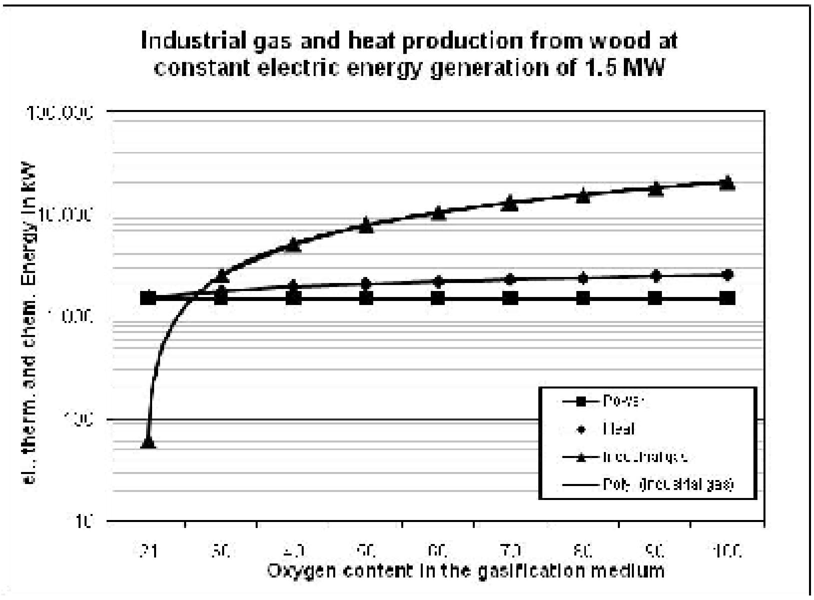

Fig. 4: Energy supply based on wood (F1) with constant power generation

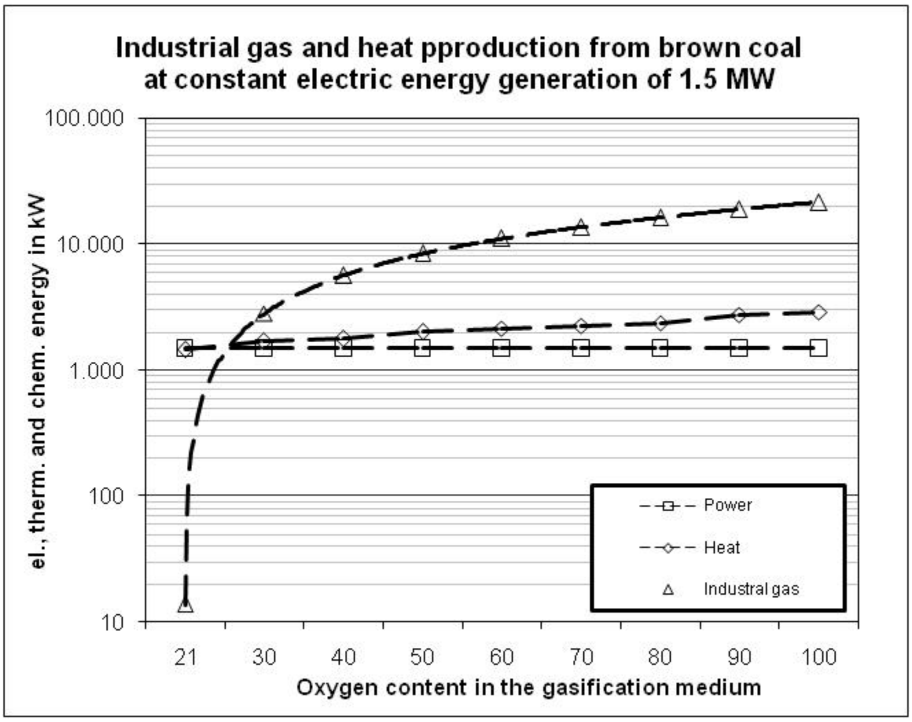

Fig. 5: Energy supply based on DBC (F2) with constant power generation

Figs. 4 and 5 show the results of the variant calculated for the production of industrial gas, heat and electric energy from wood (F1) and coal (F2) as a function of the oxygen content in the gasification medium, at a constant electric energy generation of P_{elt} = 1.5 MW and variable industrial gas production Q_{chem}.

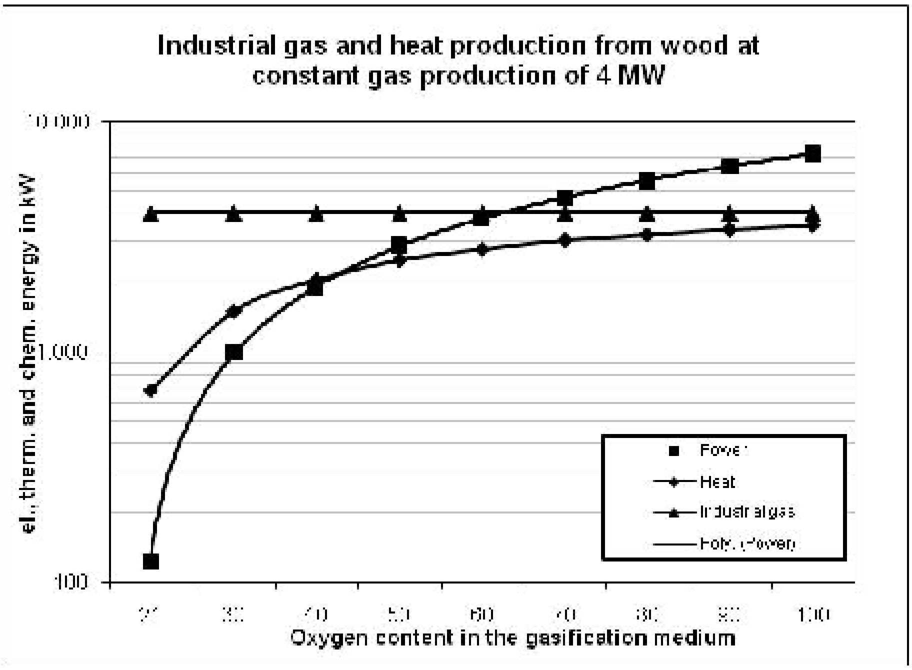

Fig. 6: Energy supply based on wood (F1) with constant gas production

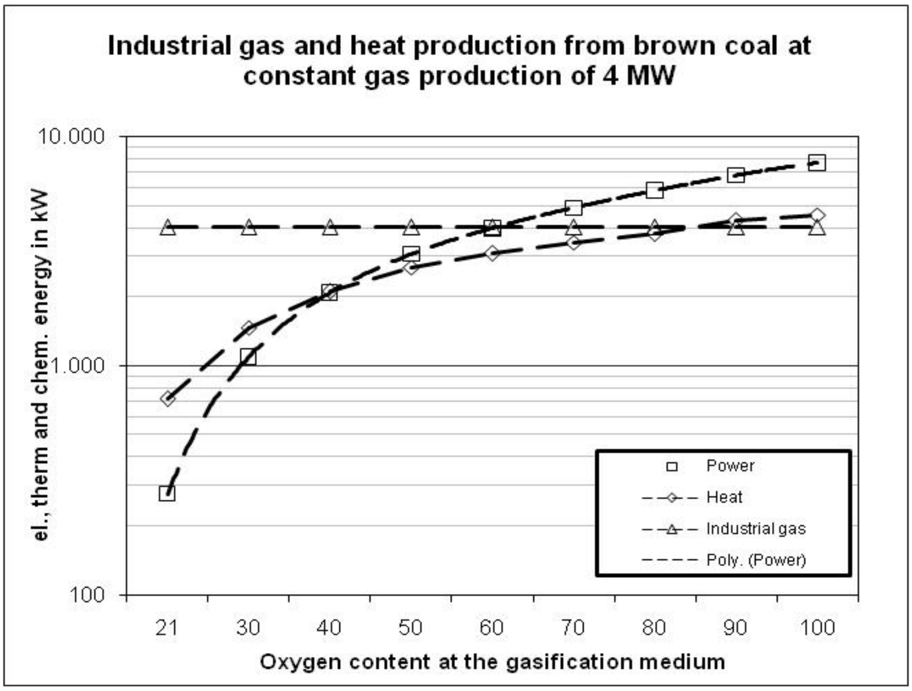

Fig. 7: Energy supply based on DBC (F2) with constant gas production

Further, Figs. 5 and 6 show the results of the calculations for a constant industrial gas production of Q_{chem} = 4 MW and variable electric energy generation $P_{elt.}$

Figs. 4 and 5 show that at constant electric energy generation of P_{elt} = 1.5 MW with the CombiPower process, the energy contained in the fuel is almost only converted into electric energy and heat. The variation of the O_2 content in the gasification medium allows the control of the industrial gas produced: the higher the O_2 content is, the higher are the combustion rate and the quantity of industrial gas.

On account of the lower water content and the higher calorific value, the use of DBC is more effective than wood in energy terms. With O_2 enrichment to 100 %, it is possible to produce around 6 t/h industrial gas with an average caloric value of H_u = 9 MJ/kg (wood) or 12.5 MJ/kg (DBC).

At a constant industrial gas production of Q_{chem} = 4 MW and regular air, the energy contained in the fuel is almost exclusively converted into industrial gas and heat (Fig. 6 and 7). With an increase of the O_2 content in the gasification medium, the surplus fuel gas can be used for generating electric energy. It should be noted that the generation of electric energy is tied to the rating of the installed district power and heating stations and only a certain partial load variation per type of district power and heating station is possible. Table 4 shows the electric energy generation for wood (F1) and coal (F2) as examples for various O_2 contents and the necessary number of district power and heating stations (P_{elt} = 1.5 - 1.9 MW/district power and heating station).

To compare the efficiency of energy conversion for wood and coal in operation with standard air and with an increased O_2 content, the exergistic efficiency was determined in accordance with [2]. This is defined as the quotient of the sum of the exergy flows produced and the sum of the exergy flows consumed:

$\eta_{exerg} = (E_{chem(Ind)} + P_{elt} + E_Q)/(E_{chem(BS)} + P_{eig})$

where

$E_{chem(Ind)}$ = exergy flow of the industrial gas
P_{elt} = exergy flow of the electric energy
E_Q = exergy flow of the heat
$E_{chem(BS)}$ = exergy flow of the fuel
P_{eig} = exergy flow of the electric energy requirement

The efficiency rates calculated according to the above are shown in Fig. 8 and 9 for the variants constant electric energy generation and industrial gas production.

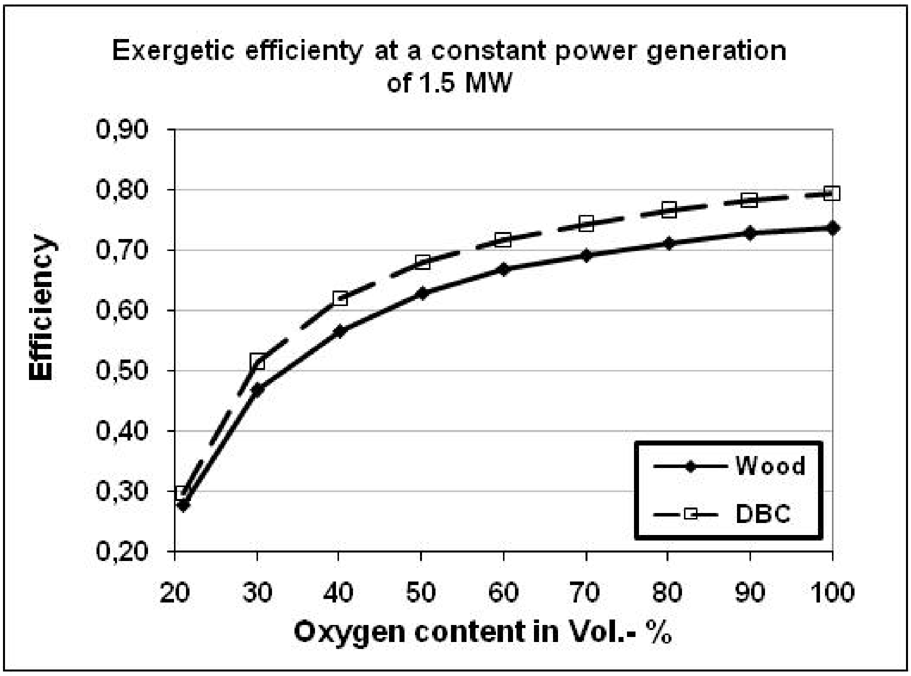

Fig. 8: Exergetic efficiency (quantity of industrial gas variable)

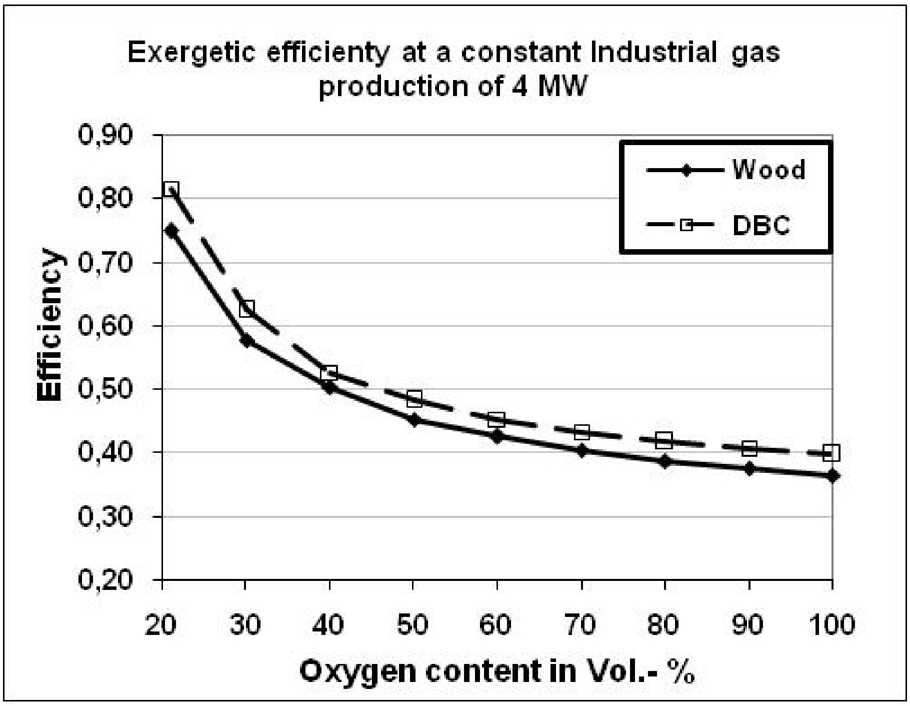

Fig. 9: Exergetic efficiency (quantity of industrial electric energy variable)

Allowing for a conversion efficiency of the district power and heating station of around 35 % relative to the fuel gas at the entry connections of the combustion engine, in standard air operation and with constant electric energy generation, η_{exerg} is calculated as 28–30 %. As this is essentially utilized thermally, the industrial gas additionally produced with the increase in the O_2 content does not lead to any further significant conversion losses (heat losses were not taken into account). It follows that with such a power-fuel combination the energy yield, relative to the fuel used, rises with increasing O_2 content in the gasification medium.

At constant industrial gas production, in standard air operation, only a negligible amount of electric energy is generated. If the O_2 content of the gasification medium is increased, commensurately more electric energy can be recovered from the fuel used. Corresponding to the curve shown in Fig. 9, this leads to a deterioration in the overall efficiency or to an apparent decrease in the energy yield. In fact, however, the additionally generated electric energy can be applied as pure exergy in many cases (e.g. to cover peak loads), so that no deterioration in the energy yield is registered.

3. Feasibility Studies

The variants considered so far (constant electric energy generation and constant industrial gas production) do not permit any conclusive evaluation, and for this reason an initial economic evaluation of the process is conducted below.

This requires an economic assessment with inclusion of appropriate criteria. The type of the fuel used is crucial. In Germany, providing the Renewable Energy Act applies, e.g. in the case of untreated wood, for the plant size described above, a statutorily guaranteed power acceptance rate of around twice the current market price can be obtained. For the heat and the industrial gas produced, standard market prices are assumed.

Important for the economic efficiency of the CombiPower process is access to a district heating network so that the heat recovered can be fed into the network over almost 5,000 to 6,000 full load hours.

The following parameters were considered in the feasibility study:

- type of fuel
- oxygen content in the gasification medium
- plant operation with constant electric energy generation of P_{elt} = 1.5 MW or constant industrial gas production of Q_{chem} = 4 MW.

Table 5: Basic data feasibility study

Basic data for the feasibility study	spez. Werte	Dimension
Investment costs (specific)	3 750	€/ kW
Investment allowance on new investments	25.0	%
Rate of interest on the capital invested	5.0	%
Period of depreciation for plants and machinery	10.0	a
Period of depreciation for building and ancillary	25.0	a
Remuneration for electric energy generated from untreated wood i.a.w. REA	163.4	€ / MWh
Remuneration for electric energy generated from standard fuels (no. RFA)	80.0	€ / MWh
Fuel costs for wood and coal according to specification	50,0	€ / t
Power costs for plant requirement at 100 to 300 kW	80.0	€ / MWh
Selling price for heat at around 1.7 to 2.0 MW	25.0	€ / MWh
Selling price for industrial gas at 8.0 MW	30.0	€ / MWh
Operating hours for power generation-varies between 7,000 and 8,000	7 500	h / a
Operating hours for heat generation-varies between 4,000 and 6,000	5 000	h / a
Operating hours for industiral gas production-varies between 5,500 and 7,500	6 500	h / a
Labour for plant operation	10	VBE / a
Plant management	1	VBE / a
Labour costs/production	28 000	Euro / VBE * a
Labour costs/ plant management	40 000	Euro / VBE * a
Ancillary labour costs (relative to the total labor costs)	5.0	%
Service and maintenance relative to the investment total for (P&M)	2.0	%
Insurance relative to the investment total	1.0	%

Interest, depreciation periods, receivables, etc. were not taken into consideration as variables owing to the complexity of the resulting calculations and are listed in Table 5. The value for the remuneration for the electric energy (163.4 €/MWh) is based on a constant generation of P_{elt} = 1,500 kW using wood as a fuel. If the generation of electric energy increases with constant industrial gas production of Q_{chem} = 4 MW, the rate of remuneration per MWh changes in accordance with the REA as shown in Table 6.

Table 6: Basic data for the remuneration for the electric energy with the use of wood (F1) in compliance with the REA

O_2 content in %	30	40	50	60	70	80	90	100
$P_{elt.}$ [kW]	998	1879	2880	3785	4647	5517	6401	7237
Remuneration [€/MWh]	170.9	160.7	156.6	154.8	153.7	153.0	144.8	138.4

The diagrams based on the feasibility calculations in Fig. 10 and 11 show the results following variation of the fuel type and costs, the O_2 content (standard air operation, 50, 70 and 90 % O_2), and for plant operation with constant electric energy generation or industrial gas production. For better understanding, selected results are listed in Table 7.

Table 7: Production costs and earning for wood (F1) and coal (F2)

Process variant	Fuel	Fuel costs [€/t]	Spec. production costs for power [€/MWh]	Spec. production costs for industrial gas (O_2-50%) [€/MWh]	Earnings (O_2-50%) [€/year]
$P_{elt.}$ = 1.5 MW (const.)	Wood	50	148.67	20.85	1 067 820
	Coal	50	135.02	16.12	577 660
-	-	-	Spec. production costs for industrial gas [€/MWh]	Spec. production costs for power at O_2 = 50% [€/MWh]	-
4 $MW_{chem.}$ (const.)	Wood	50	50.15	73.93	1 633 148
	Coal	50	45.66	59.32	407 660

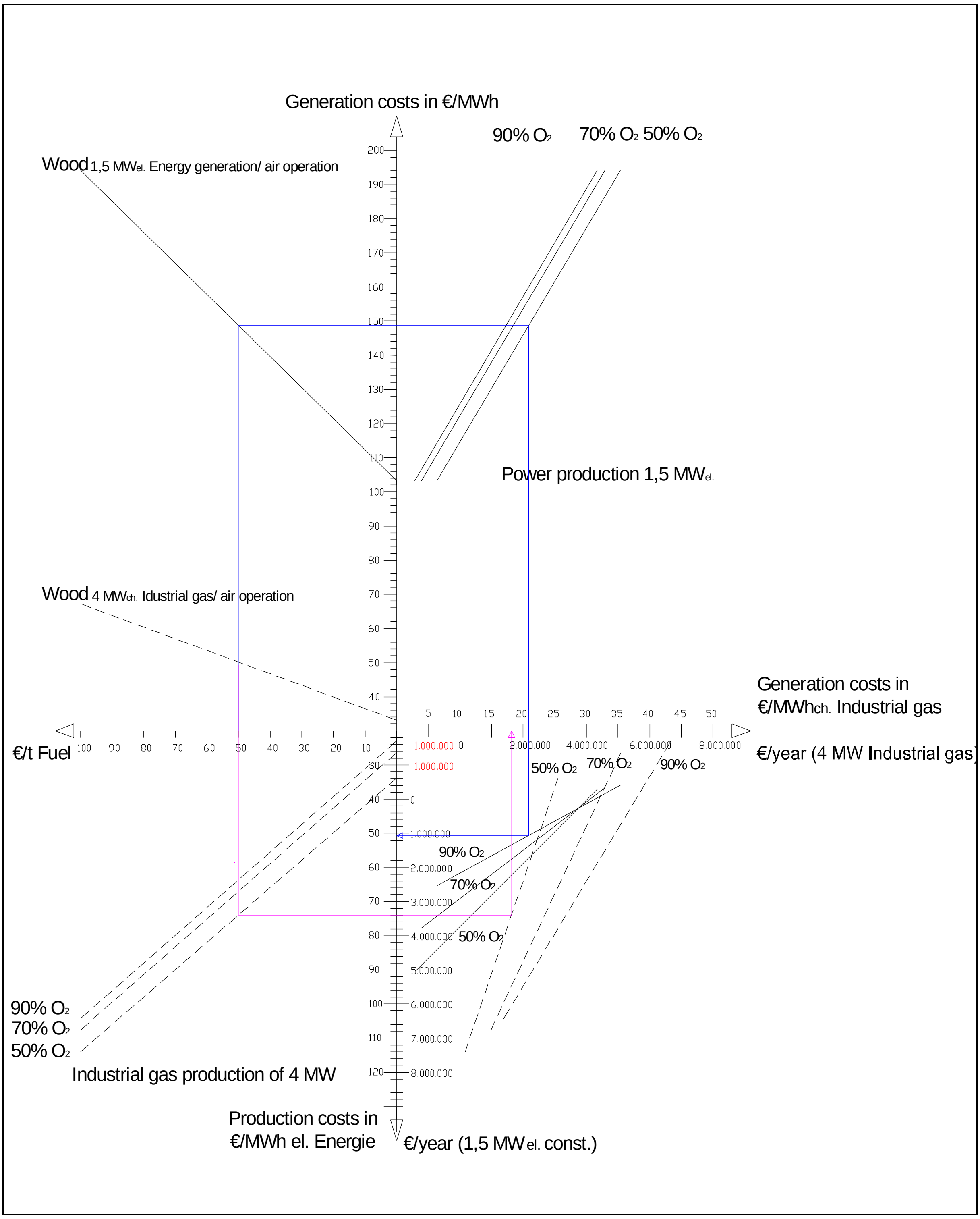

Fig. 10: Feasibility study for wood as fuel (F1)

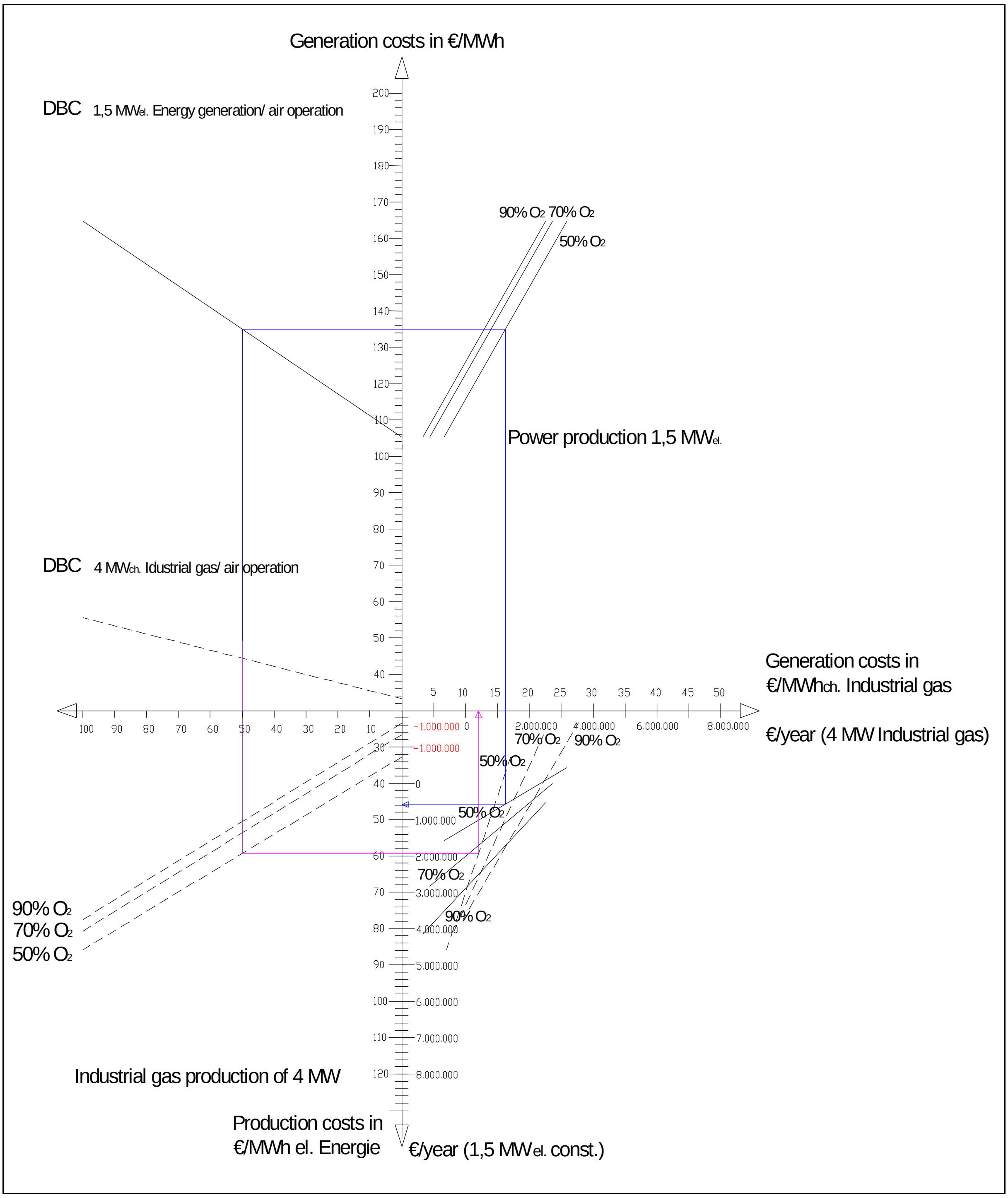

Fig. 11: Feasibility study for DBC as fuel (F2)

Despite the lower specific production costs for the electric energy and industrial gas, the earnings achieved with the use of dried brown coal (DBC) are around 40 % lower compared to those obtained with wood as the fuel. This is influenced significantly by the rate of remuneration for the generated electric energy, which stands at around 163.40 €/MWh for wood as a fuel in accordance with Germany's Renewable Energy Act and at a market price for electric energy of 80.00 €/MWh for DBC. For the variant with constant industrial gas production, operation with wood as the fuel is more favourable in economic terms despite higher production costs on account of the remuneration specifications in the Germany's Renewable Energy Act.

With regard to the comparison of the process variants “CombiPower” or “CombiPower-Plus”, it is clear that at present the CombiPower process can only be operated cost-efficiently with untreated wood at reasonable fuel prices of 40 to 60 €/t (DS 18 %) and with the statutorily assured remuneration as specified in Germany’s Renewable Energy Act. It is also clear that plants with a higher efficiency, in this case with oxygen enrichment of the gasification medium, are more cost efficient.

In the same way as above, the production costs for the exclusive generation of electric energy and the production of industrial gas can also be evaluated (Table 8).

Table 8: Production costs for the generation of electric energy only or industrial gas only

	Oxygen content	O_2-21 Vol.-%		O_2-50 Vol.-%	
	Fuel	Wood	Coal	Wood	Coal
100% Electric energy	P_{elt} in kW	1 500	1 500	4 278	4 469
	spec. production costs in €/MWh	146.53	134.57	102.44	87.11
100% Industrial gas	Q_{chem} in kW	4 300	4 300	12 226	12 740
	spec. production costs in €/MWh	45.58	41.34	29.77	24.71

Here it can be seen that the use of DBC as fuel is more favourable, the specific production costs being lower in both cases. The reason for this is the higher caloric value of the coal and resulting lower quantity of fuel required to achieve the same plant performance.

For the straight generation of electric energy, the use of wood is more economic on account of the REA remuneration regulations. With the currently achievable sales revenue of 80 €/MWh for electric energy, no economic operation is possible with coal as the fuel. The combined generation of electric energy and heat and the production of industrial gas is necessary for the economic operation of the CombiProcess with coal as a fuel.

For the exclusive production of industrial gas, the use of coal is preferable. It should be noted for pure industrial gas production, Germany‘s Renewable Energy Act does not apply and therefore wood is not the preferred fuel.

The conclusions from the calculations are that both the CombiPower and the CombiPower-Plus process can be operated economically with different fuels. General conditions such as location, access to an existing district heating power station, type of output streams, rates of remuneration for power and other energies specified in statutory regulations, etc. have considerable influence on their cost-efficient operation and must be taken into careful consideration.

References

[1] www.tescon.de/ rohoel.gif

[2] Baehr, H D.: Thermodynamik. Springer- Verlag, (8. Auflage) Berlin Heidelberg 2002

[3] Rebhan, E. u.a.: Energiehandbuch-Gewinnung, Wandlung und Nutzung von Energie. Springer- Verlag, (8. Auflage) Berlin Heidelberg 2002

[4] VER GmbH: Studie zur Entwicklung der CombiPower-Verfahrens 2005, firmenintern