COBEM2005-0045 – METHODOLOGY FOR THE OPTIMZATION OF BIOMASS GASIFICATION POWER PLANTS

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Abstract. *Biomass is a plenty fuel in several regions of the world. Particularly in Brazil biomass contributes to 22% of the primary sources. However, its role in electric power generation is not fulfilled in accordance with its availability, being the sugar cane bagasse the residue most used for this application. Besides the biomass found in the form of residues, there is that specifically cultivated to serve as fuel, the so called energy forests. The availability of high productive land in Brazil, due the privileged weather, is, doubtless, a great incentive to the production of alternative and renewable fuel sources, such as alcohol and biodiesel. This work presents an optimization method to be applied in the preliminary design of biomass fuelled power plants which are going to use energy forests as fuel source. The method is based on that presented by Prasertsan and Krukanont, (2003), which has been developed for a direct biomass firing plant. In addition to carry out a preliminary analysis of the economic feasibility of the plant, the method shown in this paper allows the user to analyze the influence of the carbon credits on the investment.*

Keywords: *Biomass, Gasification, Optmization, Gas turbine, Combined cycle*

1. The Biomass Integrated Gasfication Combined Cycle

The biomass integrated gasification combined cycle, BIGCC, is made of two basic elements: the gasification island, which includes fuel pre-processing machinery and feeding into the reactor; the reactor itself, inside which the gasification reaction takes place, resulting in gas and ash; and finally the conventional combined gas/steam cycle. Figure 1 shows the schematic of the topping part (gasification system and gas turbine engine) of a BIGCC system.

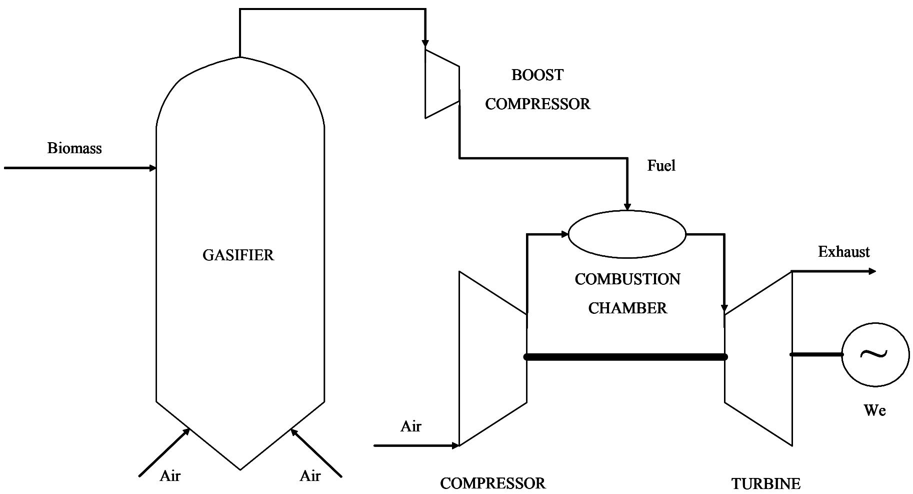

Figure 1 – Basic scheme of BIGCC system

The BIGCC system is seen as one of the best alternatives for the use of biomass as fuel due to the high efficiencies achieved by combined cycles. When operating on natural gas, a combined cycle can reach 60% ISO efficiency. Furthermore, the high power density of gas turbine engines is one of the main advantages of these type of prime movers.

The gas resulting from the gasification process has a calorific value between 3 and 11 MJ/kg. This figure depends upon several parameters, being decisive the type of oxidant, which can be either air, a mixture of air and steam, or oxygen, McKendry, (2002). When compared to the natural gas, the calorific value of the gas produced from biomass gasification, is much lower. As the gas turbines are designed to operate on high calorific value fuels, such as Diesel oil, natural gas, and kerosene, which calorific values range from 40 to 45 MJ/kg, the use of a low specific energy content gas can lead to instabilities on the engine, mainly to compressor surge. These matters and the proposed solutions have been well discussed elsewhere, Larson; Svenningosn; and Bjerle, (1989)

2. The National Program of Incentive to Alternative Energy Sources

The National Program of Incentive to Alternative Energy Sources, known as PROINFA, was created in 2002 and officially launched on March 2004. The PROINFA ensures a power purchase agreement of 20 years between the investor and the government owned electricity company ELETROBRAS. Three energy sources have been contemplated: wind power plants, small hydro power plants, and biomass fuelled power plants.

The economic values for the energy generated from biomass power plants are the following[1]:

- Sugar cane bagasse: R$ 93.77/MWh (US$ 31.79/MWh)
- Rice husk: R$ 103.20/MWh (US$ 34.98/MWh)
- Wood: R$ 101.35/MWh (US$ 34.36/MWh)
- Landfill gas: R$ 169.08/MWh (US$ 57.32/MWh)

A comparison between the figures established within PROINFA and those assessed through the methodology herein will give a first idea of the economic feasibility of the use of biomass fuels together with advanced technologies for electric power generation.

3. The optimization of the power and the maximum cost of fuel to turn a BIGCC into an economically feasible project

Defining the cultivated area of the energy forest is one of the challenges of a biomass power plant project. This parameter has a deep impact on the final cost of electricity.

Thus, it is of fundamental importance to set the balance between the power plant size and the cultivated area, aiming on reaching a reasonable cost of the biomass to fulfill the financial expectations of the investors. This is, therefore, an optimization problem.

The method herein described is based on that developed by Prasertsan and Krukanont, (2003). Those authors present an optimization routine for a cogeneration steam cycle biomass power plant. The variation presented undergone two basic modifications: (i) the the methodology has been adapted to BIGCC cycles; and (ii) the variable that takes into account the installed capacity has been substituted by another, which considers the sale of carbon credits.

It has been assumed that the power plant is located at the centre of the plantation. This situation can be applied to a power plant approximately equidistant from its suppliers (Figure 2).

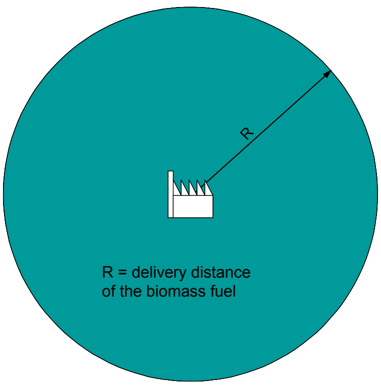

Figure 2 – Assumption made for the location of the power plant and the format of the area of the plantation

4. The optimization methodolgy

The thermal efficiency of a combined cycle, η_{CC}, is defined as:

$$\eta_{CC} = \frac{E}{Q_B} \quad (1)$$

where:

E is the electric power, MW

Q_B is the heat input through fuel, MW

The variable Q_B is defined as:

$$Q_B = \dot{m}_B PCI \quad (2)$$

where:

$\dot{m}_B$ is the fuel mass flow rate, kg/s

PCI is the lower calorific value of the fuel, kJ/kg.

The fuel mass flow rate can be expressed as follows:

[1] Exchange rate: US$ 1.00 = R$ 2.95.

$$\dot{m}_B = \frac{\psi \pi R^2}{t} \qquad (3)$$

where:
Ψ is the energy forest productivity, ton.km^{-2}.ano^{-1}
πR^2 is the planted area, km^2
t is the operating time of the power plant, given by the product between the capacity factor and the number of hours in one year, 8760 hours.

The economic analysis is based on the net present value, *NPV*, method considering constant currency. Thus, the annual cash flow, *CF*, is the difference between the annual income revenue, *IN*, and the annual expenses, *OUT*:

$$CF = IN - OUT \qquad (4)$$

Some of the electricity generated is used within the power plant to move pumps, electrical motors, for local lighting, etc. Therefore, it is fair to consider an exportation factor, fe, which represents the ratio between the electric power available to the grid and the gross electric power generated by the plant.

Considering now the sale of carbon credits, a factor regarding the revenues from this sale must be added to income revenue. Hence:

$$IN = tE\left(f_e p_e + f_C p_C\right) \qquad (5)$$

where:
f_e is the electric power exportation factor
p_e is the electric energy tariff, ¢/kWh
f_c is the CO_2 emission factor, corresponding to the avoided emission due to the use of a renewable source, kgCO_2/kWh
p_c is the market price of one ton of CO_2, ¢/teqCO_2

Thus:

$$IN = \eta_{CC} \psi \pi R^2 PCI\left(f_e p_e + f_C p_C\right) \qquad (6)$$

The annual expenses are represented by the sum of the following variables: biomass purchase cost, C_W, biomass transportation cost, C_t, labour cost, C_l, and the operation and maintenance costs, $C_{o\&m}$, herein represented as a percentage of the capital cost of the power plant. Thus:

$$OUT = C_W + C_t + C_l + C_{o\&m} \qquad (7)$$

$$C_W = \int_0^R C_{WS} \psi \left(2\pi R\right) dR = C_{WS} \psi \pi R^2 \qquad (8)$$

$$C_t = \int_0^R C_{ts} \psi \left(2\pi R\right) R dR = \frac{2 C_{ts} \psi \pi R^3}{3} \qquad (9)$$

$$C_l = \sum_{u=1}^{N} \left(C_{ls} N\right)_u \qquad (10)$$

$$C_{o\&m} = k_{o\&m} I_{total} \qquad (11)$$

where:
C_{WS} is the unit cost of the undelivered biomass, ¢.ton^{-1}
C_{ts} is the unit cost of the biomass transport, ¢.ton^{-1}.km^{-1}
C_{ls} gross salary per capita of plant personnel, US$.person^{-1}.ano^{-1}
$k_{o\&m}$ is the operation and maintenance index
I_{total} is the total capital cost of the power plant, given by $I_s E$
N number of persons working directly for the power plant.

Due to the complexity of an economic model which involves all the parameters related to the plant's construction, in this work it is assumed that the invested capital comes from only one source and that the capital cost is expended in equal installments along the life of the plant. Thus, the cash flow equation is found inserting equations (6) to (11) in equation (4).

The expression for the net present value is found to be:

$$NPV = f_a CF - I_{total} \tag{12}$$

where:

$$f_a = \frac{(1+i)^n - 1}{i(1+i)^n}$$

i minimum rate of return, MRR, or discount rate
n life of the plant, in years.

Assuming that the MRR is known, and making $NPV = 0$, the expression for the calculation of the unit cost of the biomass is then found:

$$C_{WS} = -\frac{\sum_{u=1}^{N}(C_{ls}N)_u}{\psi\pi} R^{-2} - \frac{2}{3}C_{ts}R + \eta_{CC}PCI\left[f_e p_e + f_C p_C - \frac{I_S}{nt}\left(k_{o\&m} + \frac{1}{f_a}\right)\right] \tag{13}$$

Which can be re-written in the following simplified form:

$$C_{WS} = \alpha R^{-2} + \beta R + \gamma \tag{14}$$

The optimum distance (radius), R_o, for collecting the biomass is found when $dC_{WS}/dR = 0$, hence:

$$R_o = \left(\frac{2\alpha}{\beta}\right)^{1/3} = \left[\frac{3}{\psi\pi C_{ts}}\left(\sum_{u=1}^{N}(C_{ls}N)_u\right)\right]^{1/3} \tag{15}$$

Hence, the optimum size of the plant, E_o, on the basis of power, MW, can be calculated:

$$E_o = \frac{\eta_{CC}\psi\pi R_o^2}{t} PCI \tag{16}$$

And the maximum viable price of the undelivered biomass is given by:

$$(C_{WS})_o = \alpha R_o^{-2} + \beta R_o + \gamma \tag{17}$$

5. Comments and results

According to the methodology just described, two distinct situations can occur. The first regards the market as it is nowadays, what means a high cost of capital for the proposed technology, i.e., the integration of gasification and gas turbine combined cycles. The second situation regards the adaptation of the cost of capital to fit the market interests, given the electricity tariff, the transportation costs, and the desired rate of return.

In the first case, a positive value of the optimum biomass cost, $(C_{WS})_o$, is the first indication of the economic feasibility of the project. On the other hand, a negative value of the biomass cost means that the power plant is being paid for the use of the fuel, and not paying for it. The second parameter that indicates feasibility of the plant is the biomass cost. If its value is between zero and the maximum price that would make the project feasible, then the project deserves further analysis.

In the second situation, i.e., given the market parameters – the electricity tariff, the transportation costs, the desired rate of return, and the market price of the fuel – one wants to know the capital cost that would suit it, then an iteration could be carried out in order to find the capital cost that allows the viability of the project.

A third way of using the methodology above described is the usual one, which is the calculation of the cost of energy, CoE, given the technical and economic parameters.

6. The performance of BIGCC cycles compared to conventional combined cycles

Before going into the details of the economic analysis, it is necessary to carry out a brief discussion on the thermodynamic performance of the proposed cycle, followed by a comparison between the BIGCC system and the conventional natural gas fired combined cycle.

These two power plants have been simulated using the commercial package GateCycle®, which is capable os simulating a wide variety of thermal power cycles using either solid, liquid, or gaseous fuels.

The sensitivity of the power plants to the pressure ratio of the gas turbine, *PR*, and the turbine entry temperature, *TET*, has considered a fixed value of the polytropic efficiency[2] for both, compressor and turbine, being respectively 89% and 90%. These figures are in good agreement with those published in the literature and represent average values for modern gas turbine components, Cohen; Rogers, and Saravanamuttoo, (1996);Walsh and Fletcher, (1998). The pressure loss in the combustor has been assumed constant, 5%, for the range of *PR* and *TET* considered, and the combustion efficiency has been assumed to be 99%, in accordance with the literature, Lefebvre, (1998). For cycles that use gas/gas heat exchangers, the effectiveness was assumed to be 70%. For the steam turbines, the assumed efficiency is 85%, also in agreement with the literature, Spencer; Cotton; and Cannon, (1974). The pinch-point in the heat recovery steam generator was chosen 15°C, as suggested by, Dechamps, (1999).

Aiming to generate a wide performance map, the pressure ratio ranges from 3 to 30, and the turbine entry temperature ranges from 1100K to 1600K. Commercially available gas turbine engines (Table 1) have also been included in the simulations. The choice of these models has tried to represent the main manufacturers and includes small, medium, and big engines, and their performance data can be found in GateCycle® library of engines. The data in Table 1 is for the engines operating on their design fuel.

It is worth mentioning that the minimum value of steam quality was set to a conservative 0.90 and the efficiency of the gasification system was assumed 75%, based on Bridgwater, (1995);Larson; Svenningosn; and Bjerle, (1989).

Yet in Table 1, it is possible to notice the superior performance of the aerodereived models (LM2500PE, LM6000PA e RB211). This is because these turbines work at higher pressure ratios and turbine entry temperatures.

Table 1 – Commercial models used in the simulation of the BIGCC cycles [Source: International Turbomachinery Handbook 2001/2002, (2001)]

Model	Manufacturer	Power MW	Heat Rate kJ/kWh	Efficiency %	PR	TET °C
Typhoon	Alstom Power	5.05	11,915	30.21	14.3	1,112
LM2500PE	GE	22.72	9,824	36.64	18.0	---
LM6000PA	GE	40.21	8,879	40.54	28.1	---
501-KB7	Rolls-Royce	5.27	11,819	30.45	13.5	---
RB211	Rolls-Royce	29.43	9,534	37.75	21.6	---
W251B11/12	Siemens Westinghouse	49.50	11,025	32.65	15.3	---

Regarding the fuel type, Figure 3 shows that the engine works better on its design fuel, provided it does not go lower than the limit established by the manufacturer. The specific work of the BIGGT cycle is higher due the larger fuel mass flow rate, which is added to the air mass flow rate, allowing the turbine to generate more power.

Figure 4 shows the performance of BIGCC sytems. In this figure, for the commercial engines it has been assumed that the compressor bleed equals the mass flow rate of fuel injected. This was done to avoid convergence problems of the software, for the models were running in off-design conditions, and the compressor tends to move toward the surge. That explains the little variation of specific power when compared to Table 1 figures.

Still in Figure 4, it is interesting to observe that the efficiencies of the commercial systems suffer a significant drop due to the large bleed from the compressor, and also due to the presence of the gasification island, which penalizes the efficiency of the whole cycle. The gasification island imposes a considerable penalty to the system, since the compression of the hot gases to be injected into the combustor can reach 20% of the gross power of the plant.

[2] Refer to Cohen; Rogers, and Saravanamuttoo, (1996) and Walsh and Fletcher, (1998) for more information on the usage of polytropic efficiency and isentropic efficiency on gas turbine power plant simulations.

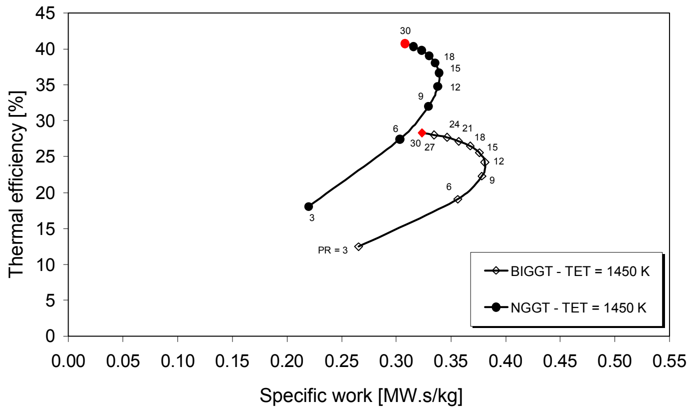

Figure 3 – Performance comparison of OPEN cycle gas turbines running on different fuels, the natural gas, NGGT, and the biomass derived gas, BIGGT

The literature, Consonni and Larson, (1996), usually mentions the aeroderived engines as the most promising to be applied in BIGCC systems due to their high pressure ratios and turbine entry temperatures. However, Figure 4 shows the opposite. The explanation is that, due to the high pressure ratios of the aeroderived, the fuel compressor will demand more power.

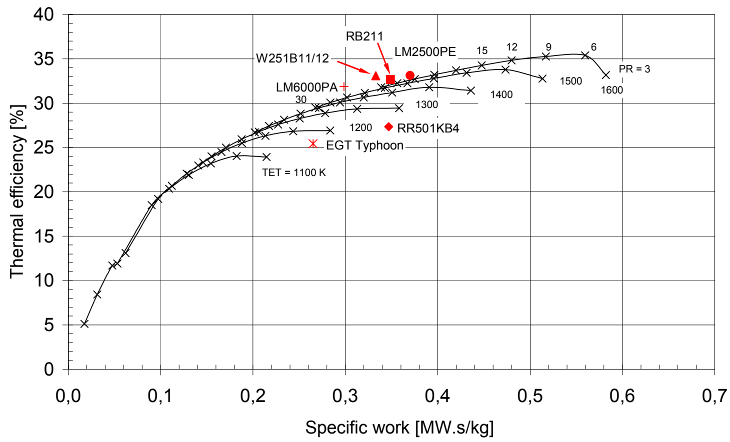

Figure 4 – Performance of BIGCC systems operating on biomass derived gas obtained by atmospheric gasification

7. The economic optimization of the BIGCC systems

The upper part of Table 2 shows the parameters used as input for the optimization process. Firstly, these parameters have been assumed as *datum* and the optimum cost of biomass, the optimum biomass collection distance and the maximum power have been calculated. The capacity factor and the electricity exportation factor are in accordance with the open literature. Despite, the little experience on the operation of integrated gasification/gas turbine plants, it is believed that this technology is not too far from commercial availability. The efficiency was taken from Figure 4.

The biomass productivity and its transportation cost were estimated based on the data presented by Carpentieri; Larson; and Woods, (1993);Pereira et al., (2000). The life of the plant and the electricity tariff were assumed to be same adopted in the National Program of Incentive of Alternative Energy Sources, PROINFA, Ministério de Minas e Energia - MME, (2003).

The results indicate that a BIGCC project in Brazil, within the framework of PROINFA and given the costs involved, is not economically feasible. Despite the attractive potential, 66.3 MW, the project presents a negative cost of fuel, meaning that the power plant would have to be paid by the fuel, and nor pay for it.

One of the most important parameters that define the economical feasibility of a project is the cost of capital. In the case studied here, it is twice the average cost of capital of a conventional natural gas fired combined cycle. Figure 5 shows that the cost of capital for a BIGCC system has to be between US$450/MW and US$ 480/MW to make such project feasible, if the cost of fuel is zero. Carpentieri; Larson; and Woods, (1993) estimated that the cost of wood from an energy forest in the Northeastern region of Brazil would approximately US$ 1.5/GJ, taking this value into the model, the specific cost of capital should be between US$ 300/MW and US$ 400/MW.

Table 2 – Input parameters for the optimization and results

Capacity factor, %	90
Electricity exportation factor, %	90
Thermal efficiency of the power plant, %	33,1
Biomass productivity, ton/km2/year	1.900
Lower Heating Value, MJ/kg	18
Unit cost of biomass trasnportation, ¢/ton/km	50
Discount rate, %	12
Specific cost of capital, US$/kWe	2.000.000,00
O&M costs, % of the total cost of capital	6,31
Power plant life, years	20
Electricity tariff, ¢/kWh	3,4
Price of carbon credit, ¢/tonCO_2	400
Avoided emissons of CO_2, tonCO_2/kWh	4 x 10-4
Results	
Optimum cost of biomass, US$/GJ	- 8,9
Optimum biomass collection distance, km	7,3
Maximum power, MW	66,3

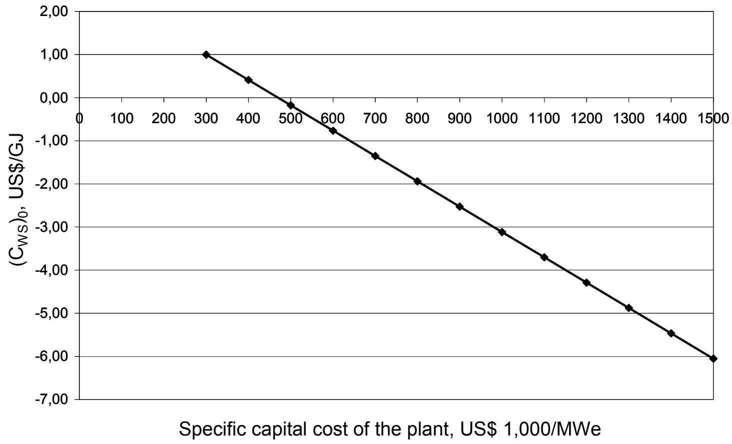

Figure 5 – Sensitivity of the optimum price of the undelivered biomass to the cost of capital of the plant

The little experience accumulated in BIGCC systems generate uncertainties with regard to the availability and the reliability of these power plants. Thus, Figure 6 shows the sensitivity of the generation potential to the capacity factor of such a power plant. From equation (15) it is possible to see that the capacity factor does not affect the optimum biomass collection distance. Therefore, it is fair to expect that the generation potential will increase when the capacity factor decreases, since the planted area will be the same, what results in constant fuel availability. The optimum price of the biomass behaves exactly in the opposite way, i.e., the lower the capacity factor, the less feasible the project.

Regarding the carbon credits, the revenue proportioned by its sale had no effect on the economic performance of the project. This happened because the base line adopted was a natural gas fired combined cycle, which already presents low CO_2 emissions.

8. Conclusion

This work presents an optimization method for biomass integrated gasification/combined cycle power plants. Based on the thermodynamic and financial parameters, the methodology calculates the maximum price to be paid for the undelivered biomass that will make such a project feasible. Although the methodology demonstrated its robustness, it represents a first approximation to assess the technical and economical feasibility of a BIGCC project.

The results from the thermodynamic simulation show a great potential of biomass as fuel for combined cycles, and highlights its advantages as a renewable and clean source of energy.

The results from the economic analysis have been compared to the economic values of PROINFA. The figures show that the high cost of capital of a BIGCC plant is the main factor against implementation. Another interesting result is that the carbon credits, with the baseline herein adopted, does not make great impact on the economics of the plant.

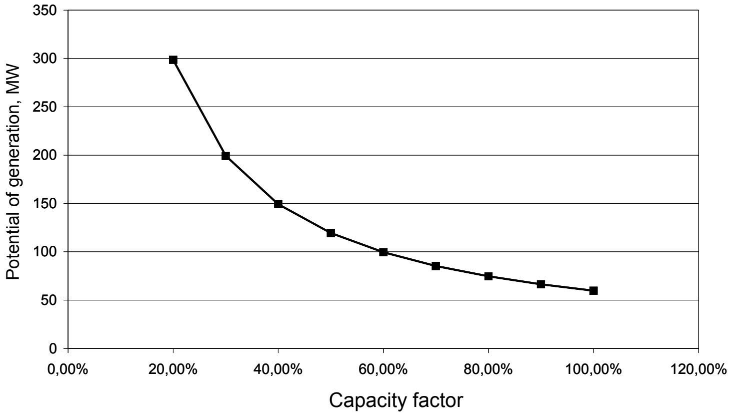

Figure 6 – Sensitivity of the generation potential to the capacity factor of a BIGCC plant

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