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# TECHNICAL AND ECONOMIC EVALUATION OF IGCC SYSTEMS USING COAL AND PETROLEUM COKE CONSIDERING THE BRAZILIAN SCENARIO

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## ABSTRACT

The increasing trend in global production of petroleum coke (petcoke) is the result of their multiple and innovative industrial applications. From this point of view and also considering the current situation of the traditional energy reserves worldwide, it is important to conduct studies in this area through analysis of the main components of the power plants utilizing this fuel (petcoke).

The main target of this study is to realize a techno-economic evaluation of IGCC (Integrated Gasification Combined Cycle) technology, using Brazilian coal, petcoke and a mix of 50% coal and 50% petcoke as fuel. In this paper, the gasification process and the combined cycle are analyzed, considering the implementation of the IGCC technology in the Termobahia power plant. Termobahia is a cogeneration combined cycle power plant, located in the Brazilian state of Bahia that produces 190 MW of electricity and 350 ton/h of steam. The steam produced is sold to an oil refinery (RLAM) located next to it. In first part of this work, the production of the synthesis gas (syngas) from coal gasification was simulated using CeSFaMBi™ software. In the next part, the syngas produced is used to analyze the power plant performance through GateCycle™ software. Finally, the obtained operational and economic parameters are compared with the actual operational parameters of the Termobahia power plant in terms of costs, fuel substitution and combined cycle performance variables, as net power, global efficiency and heat rate.

## NOMENCLATURE

| | |
|---|---|
| AFBC | Atmospheric fluidized bed combustion |
| ASU | Air separation unit |
| CCS | Carbon capture and storage |
| CeSFaMBi | Comprehensive simulator of fluidized and moving bed equipment |
| CRF | Capital recovery factor |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| COS | Carbonyl sulfide |
| FCI | Fixed capital investment |
| HHV | Higher heating value |
| HRSG | Heat recovery steam generators |
| ID | Integration degree |
| IGCC | Integrated gasification combined cycle |
| LHV | Lower heating value |
| PEC | Purchased equipment cost |

## INTRODUCTION

Nations are constantly searching for new means to ensure a reliable, economical and environmental friendly way to supply energy, leads to the formation of a diverse energy matrix which is composed of various electricity generating technologies. These technologies vary according to the conditions and characteristics of each specific site, and depend mainly on the availability of natural resources, the electricity costs and the technology.

Considering the worldwide energy scenario with proven current coal reserves and the crescent production of petcoke the implementation of IGCC technology in becoming interesting and it is receiving special attention in the last years. This technology is characterized by the conversion of fuels such as coal, biomass, and refinery residues that cannot be directly used in gas turbines, into a clean gaseous fuel that meets engine specifications and environmental emissions standards.

Moreover, currently IGCC power plants are focused on the development and implementation of CCS technology to reduce $CO_2$ emissions and increase plant efficiency, with significant reductions in generation costs [1].

In this context, this article discusses the implementation of IGCC technology considering the Brazilian scenario, and using as study case the Termobahia power plant. Initially the gasification process was analyzed using CeSFaMBi software to determine the composition of syngas. After that, it was used the GateCycle software to analyze the combined power plant cycle. The results obtained through CeSFaMBi and GateCycle interaction, are then discussed in the final part of this paper, in terms of costs, fuel substitution and combined cycle performance variables, with an emphasis on net power, global efficiency and heat rate.

## INFLUENCE AND CONSIDERATIONS IN THE USE OF SYNGAS IN A GAS TURBINE

The effects of using syngas in a gas turbine originally designed for natural gas can be determined through off-design simulation. The main constraints are the effects on the compressor surge margin and the turbine blade metal temperature.

Recent studies [2,3,4] show the influence of fundamental design parameters on performance of IGCC systems, concluding that the type of integration method significantly affects the performance and operating condition of a gas turbine.

Theoretically, the power output and the efficiency of the gas turbine increase as the integration degree (ID) decreases. However, if no major modifications of the compressor and turbine are made, the surge margin decreases and the turbine metal temperature rises. The problem becomes more severe as the ID decreases. In particular, depending on the ID, compressor surge margin may be considerably reduced when a natural gas-fired turbine is adopted in an IGCC system without any modifications. The main reason for the reduced surge margin is the increased mass flow rate at the turbine due to the relatively LHV of the syngas. The low ID design may worsen the problem because the use of an auxiliary air compressor increases the mass flow of the turbine.

The problem of turbine metal overheating can be solved by several methods, including a reduction in firing temperature and an increase in turbine coolant. Reducing the firing temperature is easier to execute but reduces system performance significantly, especially with regard to the net power output. Increasing the turbine coolant also reduces the performance moderately, but yields much greater net power output than reducing the firing temperature [5].

## IMPLEMENTATION OF IGCC SYSTEMS CONSIDERING THE BRAZILIAN SCENARIO

The viability of implementing IGCC technology using Brazilian coals or petcoke depends basically on the following factors: the initial investment for the plant built-up, the investment return and the analysis of potential factors that could appear and avoid a proper operation of the plant due to the low quality of Brazilian coals. This paper analyzes the implementation of the IGCC technology in the Termobahia power plant. The model is characterized by replacing the original fuel (natural gas) for coal and petroleum coke, in a way that it is possible to make an effective model for integration of the gasification process with the combined cycle power plant.

## CHARACTERISTICS OF TERMOBAHIA COGENERATION COMBINED CYCLE PLANT

Termobahia is a cogeneration combined cycle power plant, located in the Brazilian state of Bahia. It produces approximately 350 ton/h of steam and 190 MW of electricity, which is supplied to the Brazilian grid. This power plant was initially proposed as a way to modernize the operation of the steam supply system of the adjacent Petrobras Landulfo Alves oil refinery (RLAM) and at the same time to adopt an efficient cogeneration cycle in place of the less economic steam generation in conventional boilers. Table 1 describes the main components of the Termobahia power plant [6] and Figure 1 shows a schematic of its thermodynamic cycle.

RLAM is the oldest and second biggest refinery in Brazil, with a crude oil processing capacity of 49200 $m^3$/day. Certainly it is also the most complex Brazilian refinery, offering 17 different petroleum based products, including petcoke. And this is one of the main reasons why it was selected as a study case in this paper. Nowadays, the fuel burned in the power plant is supplied from a gas field located in the Bahia state. This region is the biggest natural gas producer in the north east of Brazil, supplying nearly 5.3 million $m^3$ daily.

Flexibility is a key feature of the Termobahia power plant, which, as well as supplying both steam and electricity, burns essentially three kinds of fuel as illustrated in Table 1 [7].

**Table 1. Main data for Termobahia combined cycle cogeneration plant**

| | |
|---|---|
| **POWER PLANT** | |
| Type | Single-shaft cogeneration with supplementary firing |
| Integrated plant design point (ºC) | 25 |
| Electrical power output (MW) | 190 |
| Net fuel efficiency (%) | 90 |
| Steam export capacity (tonne/h) | 350 |
| Fuel | Natural gas, rich gas (GT)<br>Natural gas, rich gas, Refinery gas (HRSG) |
| **GAS TURBINE** | |
| Type | Alstom GT24 |
| Shaft speed (rpm) | 3600 |
| Compression ratio | 30:1 |
| Number of compressor stages | 22 |
| Number of turbine stages | 1 HPT and 4 LPT |
| Exhaust gas temperature (ºC) | 630 |
| Exhaust mass flow (kg/s) | 391 |
| Low NOx burner type | EV |
| NOx emissions (vppm) | < 25ppm |
| **STEAM TURBINE** | |
| Type | Alstom HD1-C (1 pressure) |
| Backpressure (barg) | 42.3 |
| Shaft speed (rpm) | 3600 |
| **HEAT RECOVERY STEAM GENERATOR** | |
| Type | CMI, vertical, with one pressure level. Induced natural circulation with start up circulation pump. |
| **HP STEAM** | |
| Operating pressure (bar) | 124.4 |
| Temperature (ºC) | 567.7 |
| Temperature of hot gas after supplementary firing (ºC) max | 794 |
| Mass flow of hot gas (kg/s) | 399.4 |

In the present work it is proposed a scenario for the introduction of the IGCC technology at the Termobahia power plant and natural gas substitution by fuels such as coal and petroleum coke. Using these kinds of fuels it is possible to improve the properties of the fuel. In the analyzed Brazilian case, where coal was mixed with petroleum coke, a fuel with a small percentage of ash and moisture, compared to its initial composition, was obtained. IGCC systems can enhance the thermal efficiency and strongly reduce pollutant emissions with respect to the operation of the power plant based on natural gas and others clean coal technologies, such as, Pulverized Coal (PC), Fluidized Bed Combustion (FBC) and Direct Combustion of coal [8].

## FUEL CHARACTERIZATION

Initially it will be presented the main characteristics of the Brazilian fuels (coal, petcoke and a mixture of 50% coal with 50% petcoke) used in this analysis. Table 2 show the elemental fuel analysis that will be considered in the gasification technologies simulation [9] [10].

**Table 2. Elemental fuel analysis in gasification process simulations**

Ultimate analysis

| | CANDIOTA COAL | PETCOKE | CANDIOTA COAL / PETCOKE MIXTURE |
|---|---|---|---|
| Carbon (%) | 34.0 | 86.3 | 62.5 |
| Hydrogen (%) | 2.6 | 3.5 | 3.0 |
| Nitrogen (%) | 0.7 | 1.6 | 1.1 |
| Oxygen (%) | 8.5 | 0.5 | 4.5 |
| Sulphur (%) | 1.2 | 7.5 | 3.9 |
| Ash (%) | 53.0 | 0.6 | 25.0 |
| HHV (MJ/kg) | 13.8 | 33.6 | 25.1 |

Proximate analysis (wt. %)

| | CANDIOTA COAL | PETCOKE | CANDIOTA COAL / PETCOKE MIXTURE |
|---|---|---|---|
| Moisture (%) | 15.0 | 7.0 | 9.2 |
| Volatile | 16.4 | 19.2 | 18.6 |
| Fixed Carbon | 24.4 | 73.5 | 51.5 |
| Ash (%) | 44.2 | 0.3 | 20.7 |

## GASIFICATION PROCESS SIMULATION WITH THE CeSFaMBi SOFTWARE

The proposed gasification process modeling uses CeSFaMBi software, which is a comprehensive mathematical model and simulation program for bubbling and circulating fluidized-bed, as well as downdraft and updraft moving-bed equipment. Among these equipments, there are furnaces, boilers, gasifiers, dryers, and reactors [11].

In the gasification process simulation it was selected a circulating fluidized bed as gasifier using an oxygen/steam mixture as gasification fluid (85 % of oxygen and 15 % of steam). This technology has been successfully used in many fields, including combustion, biomass/coal gasification and oil catalytic cracking, which is the type that best fits within the possibilities of simulation gasifiers in the CeSFaMBi software, taking into account the power ranges that they can achieve.

Table 3 lists the main parameters required by CeSFaMBi software for the gasifier simulation using coke as fuel. In the tests carried out, the feed mass flow rates, the feed gas though distributor (Gasification agent) and the granulometry of the fuel fed to the gasifier were modified in order to achieve the conditions above the second turbulence limit, allowing for increased contact between particles and gases.

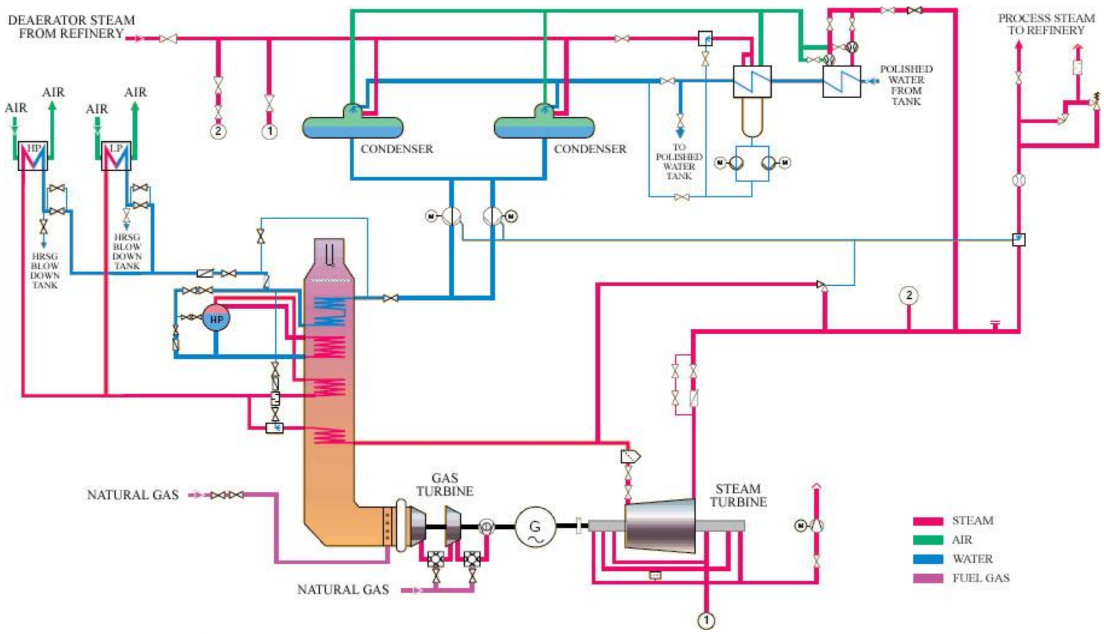


Figure 1. Simple gas turbine cycle scheme used for the thermal simulation

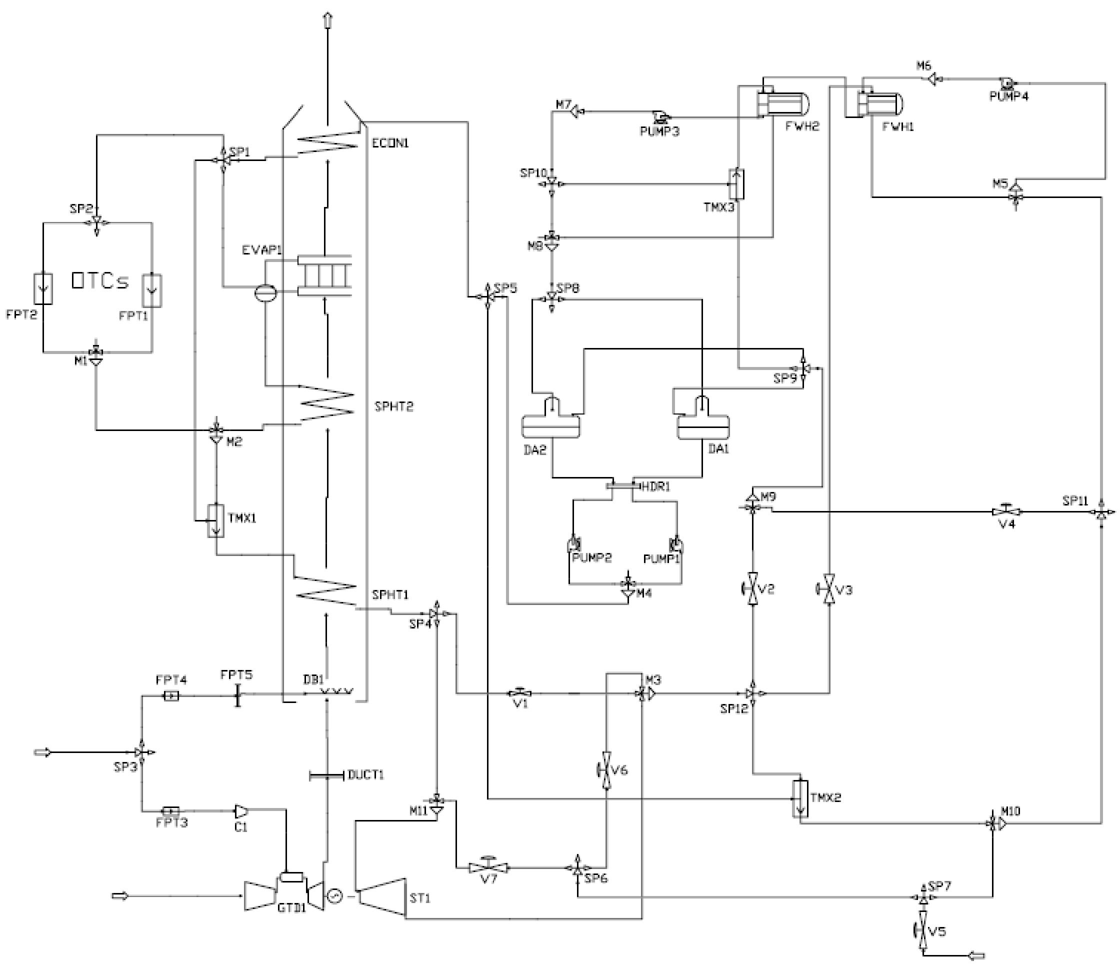


Figure 2. IGCC power plant scheme modeled on GateCycle software

Table 4 describes the gasifier efficiency and the main compounds in volumetric percentage of the synthesis gas produced from coal, pet coke and a mixture of both, using the CeSFaMBi software, without taking into account the low percentage of $H_2$, $H_2S$, $NH_3$ and $SO_2$ compounds.

The performance of a gasifier is often expressed in terms of its efficiency, which can be defined in two different ways: Cold gas efficiency and Hot gas efficiency. The cold gas efficiency is used if the gas is used for running an internal combustion engine, in which case the gas is cooled down to ambient temperature and tar vapors are removed. While, the hot gas efficiency is used for thermal applications, when the gas is not cooled before combustion and the sensible heat of the gas is also useful.

**Table 3. Key input parameters of the gasifier design**

| Parameter | Variable | Value | Units |
|---|---|---|---|
| ***STREAM CHARACTERIZATION SOLIDS AND FUEL FEEDING*** | | | |
| Apparent density, Carbonaceous | ROPESC | 750 | kg/m$^3$ |
| True density, Carbonaceous | RORESC | 1680 | kg/m$^3$ |
| Inlet mass flow rate, Carbonaceous | FMTESC | 30.0 | kg/s |
| Inlet temperature, Carbonaceous | TPESA | 298 | K |
| ***EQUIPMENT DATA - BASIC GEOMETRY*** | | | |
| ***Gasifier*** | | | |
| Bed - equivalent hydraulic internal diameter | DD | 3.25 | m |
| Freeboard - equivalent hydraulic internal diameter | DF | 3.25 | m |
| Position of main gas withdrawal | ZF | 10.0 | m |
| Position of carbonaceous fuel feeding | ZFEEDA | 2.5 | m |
| ***Distributor*** | | | |
| Number of orifices for gas/steam injection (0=porous plate) | NOD | 3000 | - |
| Diameter of orifices for gas/steam injection through distributor | DOD | 0.004 | m |
| ***EQUIPMENT DATA - CYCLONES AND RECYCLING*** | | | |
| ***Ciclone*** | | | |
| Internal diameter of cyclones | DCY | 0.8 | m |
| Height of the cylindrical part of cyclones | HCY | 1.000 | m |
| Height of the conical part of cyclones | HCYC | 1.0 | m |
| Position of recycling injection | ZRCY | 2.0 | m |
| ***STREAM CHARACTERIZATION GASES THROUGH DISTRIBUTOR*** | | | |
| ***Gasification agent*** | Mixture Oxygen (85%) + Steam (15%) | | |
| Inlet gas through distributor, Temperature | TEGID | 525 | K |
| Inlet gas through distributor, Pressure | PEGID | 180 | kPa (abs.) |
| ***ADDITIONAL OPERATIONAL CHARACTERISTICS*** | | | |
| Local Ambient Conditions | | | |
| Average pressure in the bed | POPER | 160 | kPa (abs.) |
| AVG surrounding air temperature | TAMB | 298 | K |
| Wind velocity | VV | 2.0 | m/s |

**Table 4. Synthesis gas composition (dry basis) and gasifier efficiency**

| | COAL | PETCOKE | MIXTURE (50:50w) |
|---|---|---|---|
| $CO_2$ | 12.12 | 13.15 | 12.25 |
| CO | 43.97 | 42.49 | 44.01 |
| $CH_4$ | 0.05 | 0.06 | 0.04 |
| $H_2$ | 42.61 | 43.24 | 42.91 |
| $N_2$ | 0.59 | 0.74 | 0.66 |
| $H_2O$ | 41.96 | 39.95 | 40.15 |
| HHV (MJ/kg) | 11.05 | 12.69 | 11.84 |
| Cold efficiency 57% | | Hot efficiency 81% | |

## COMBINED CYCLE SIMULATION USING GATECYCLE SOFTWARE

IGCC system simulation was carried out using GateCycle software (version 5.51). This software is a powerful tool for power plant design and analysis [12]. In the model developed for the gas turbine simulation, the Alstom GT24 (ABB NatGas 60Hx) reference was selected from the software library and the curve sets were used as calculation method. For the steam side, one has included all the components needed to build the model of the HRSGs accurately, with multiple pressure levels and also the steam turbine. Figure 2 shows the model developed in GateCycle software.

The simulation considered as ambient conditions 100.80 kPa, 26 °C and 70 % HR. In addition, the syngas composition presented in Table 4 was used as fuel for the gas turbine.

Firstly, the model developed in GateCycle used as reference the Termobahia scheme presented in Figure 1. Later, elements required to implement the IGCC technology.

Normally the capacity of an IGCC plant depends on the gas turbine model selected [13]. In this work it was proposed a plant of 190 MW, and was decided to determine the thermal input for the given net power output. For the steam cycle of the IGCC plant, a dual-pressure reheat cycle instead of the conventional assumption of a triple-pressure because this is the HRSG configuration existent in Termobahia. In order to reduce the heat losses of the gasifier, usually the gasification and power plant process are closely connected, with energy exchange between both units. The fuel supply to the gasifier is determined by the request of a net electrical output of the plant.

The model available in GateCycle for the equipments used in the combined cycle systems (steam and gas turbine, evaporators, heat exchanger, HRSG, condenser, etc.) was developed taking into account the operation parameters presented in Table 1. In this work, temperature, pressure, mass flow and clean syngas are initial parameters of the gas turbine equipment. Auxiliary losses, which could not be considered in this simplified approach, as gasifier and combustion chamber heat loss, coal treatment, operation of cooling water pumps or the syngas cleaning, were considered as 5 % of the total heat input.

## RESULTS AND ANALYSIS OF IGCC MODEL

Two syngas streams were used in the plant model developed in GateCycle: one in the heat recovery block and other furnish fuel to the gas turbine. In the first steam, pressure, temperature and mass flow information is provided for estimation of heat recovery and steam production from the gasification island. The second stream is feed with information associated with the clean syngas composition as well pressure, temperature, and mass flow.

Moreover, the power cycle using 2-level pressure for determining heat rate and efficiency of combined cycle were used to validate the thermodynamics simulations. The electric power generated is calculated and efficiency and heat rate is evaluated. Table 5 shows a comparison of the power results obtained considering the existent configuration of the Termobahia power plant and the results of the simulations when the IGCC technology was implemented on it.

**Table 5. Result of the combined cycle power plant modeling**

| Variable | Termobahia Value | Fuel | Simulations Value |
|---|---|---|---|
| Combined cycle net power [MW] | 186.80 | Coal | 183.87 |
| | | Petcoke | 185.96 |
| | | Mixture | 184.12 |
| Combined cycle global efficiency [%] | 32.91 | Coal | 28.45 |
| | | Petcoke | 29.01 |
| | | Mixture | 28.58 |
| Combined cycle Heat Rate [kJ/KWh] | 10955 | Coal | 12650 |
| | | Petcoke | 12413 |
| | | Mixture | 12592 |

## ECONOMIC ANALYSIS

In order to conduct the economic analysis of the thermodynamic cycle the purchased equipment cost (PEC) was estimated. These costs were obtained by correlations proposed by Peters and Timmerhaus [14], using data from equipment manufacturers. Table 6 shows the estimated costs based on the total plant cost percentage, and using as reference data form 2008. It is important to point out that the uncertainty range for this estimate is approximately ± 30% [15]. Additionally, Table 6 shows the distribution of fixed capital investment (FCI) and operation using the methodology proposed [16].

**Table 6. IGCC Capital Cost Estimate and Distribution fixed capital investment**

| ITEM / DESCRIPTION | TOTAL PLANT COST (%) |
|---|---|
| FUEL HANDLING, PREP & FEED | 8.21 |
| FEEDWATER & MISC. (Balance of plant) | 3.76 |
| GASIFIER & ACCESSORIES | 33.43 |
| HOT GAS CLEANUP & PIPING | 10.31 |
| COMBUSTION TURBINE (GT)/ACCESSORIES | 14.17 |
| Heat Recovery Steam Generator (HRSG), | 6.05 |
| STEAM TURBINE GENERATOR | 6.27 |
| COOLING WATER SYSTEM | 2.8 |
| ACCESSORY ELECTRIC PLANT | 2.78 |
| INSTRUMENTATION & CONTROL | 4.83 |
| IMPROVEMENTS TO SITE | 2.78 |
| BUILDINGS & STRUCTURES | 4.61 |
| ***Distribution fixed capital investment*** | |
| Total direct cost (TDC) | 78% PEC |
| Total indirect cost (TIC) | 13% TDC |
| Annual maintenance (M) | 5% PEC |

Based on the purchased equipment cost, direct, indirect and maintenance costs can be estimated. The economic analysis was developed based on the estimated capital costs, performance, fuel and operating costs of each alternative.

The assumptions used in the development of economic analysis were:

- 7008 hrs/year at 100% load (80% capacity factor).
- 2 cold starts per year.
- Property taxes.
- Insurance (included in economic analysis).
- Initial spare parts (included in capital cost estimate).
- Fixed costs: items such as plant staffing, office and administration, training, safety, contract staff, annual inspections, standby power energy costs and other miscellaneous fixed costs.
- Variable costs include items such as gas turbine, steam turbine, HRSG, gasifier, and syngas treatment system scheduled maintenance, water treatment, wastewater disposal, consumables, landfill costs, balance of plant equipment maintenance and replacements, unplanned maintenance activities, and estimated emissions allowance costs.

For a useful life of 20 years (N) and annual interest rate (i) of 12% (typical of Brazilian economic scenario), the capital recovery factor (CRF) is obtained by Eq. (1), which gives the present value in terms of the annuity, the interest rate, and the number of annuities. Table 7 shows the main parameters of the economic analysis.

$$CRF = \left[\frac{i\,(1+i)^N}{(1+i)^N - 1}\right] \qquad (1)$$

Table 7. Key parameters of the economic analysis

| O&M cost [17] | | IGCC | NGCC |
|---|---|---|---|
| Fixed | $/kW/yr | 38 | 12 |
| Variable | $/MWh | 3 | 2 |
| **Capital cost** | $/kW | 1800 | 550 |
| | | | |
| **Variable** | | **Value** | **Units** |
| Plant size | | 190 | MW |
| Useful life (Periods) | | 20 | years |
| Net present value | | 12.5 | % |
| Brazilian inflation rate 2009 [18] | | 4.31 | % |
| Capacity factor (C.F) | | 0.80 | |
| Energy output/year | | 1331520 | MWh |
| **Fuel cost [19]** | | | $/MBtu |
| Coal | Petcoke | Mixture | Natural Gas |
| 1.10 | 0.6 | 0.85 | 6.23 |

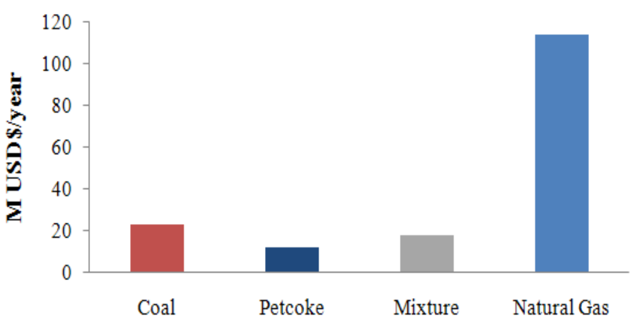


Figure 3. Annual fuel costs

Figures 3 shows the annual fuel costs for the 3 different types of fuel analyzed, highlighting in the obtained results the competitive advantages, in relation of the energy cost, of the use of petcoke as fuel compared to natural gas use.

Figures 4 and 5 show the cost of electricity by source and the levelized cost to IGCC and NGCC technologies as a function of the capacity factor, respectively. IGCC are more attractive than NGCC systems for capacity factors above 50%.

For this reason, one can conclude that it is interesting the repowering or implementation of this kind of technology on existing units, in this case, the Termobahia power plant.

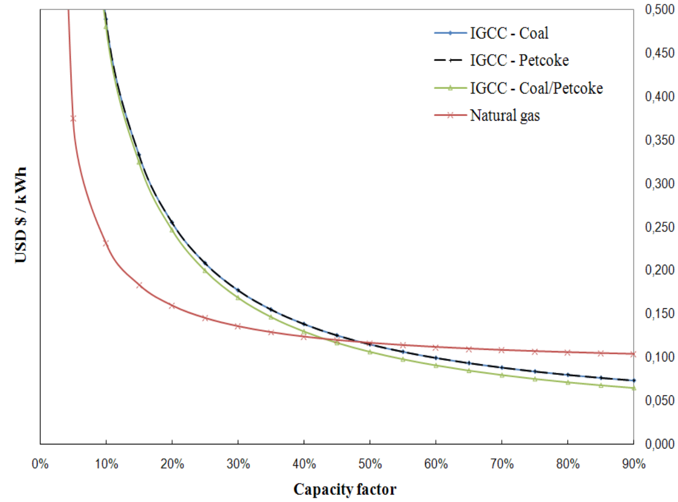


Figure 4. Cost of electricity by source

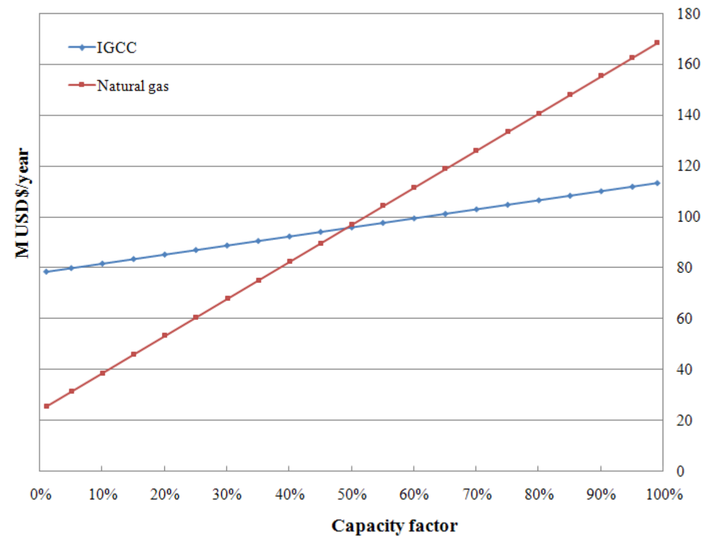


Figure 5. Levelized cost of construction to IGCC and NGCC technologies

## CONCLUSIONS

This paper showed that the incorporation of syngas as fuel in the GT technologies can significantly improve the performance efficiency of IGCC systems. The main difference found in the analyzed parameters for the 3 types of fuels used are shown in fuel consumption; this is reflected in the calorific value of fuels and in the heat rate calculated for all cases.

The implementation of IGCC technology at the Termobahia power plant is technically feasible, represents fuel cost savings and similar combined cycle global efficiency, when of the replacing the natural gas by fuels such as coal and petroleum coke. Thus, the IGCC technology represents an interesting alternative for power generation in places that have the infrastructure to transport and supply coal and petroleum coke.

 

This technology can also be seen in the Brazilian plans for expansion of energy infrastructure, through energy development plans in the short, medium and long term.

The economic analysis shows that the average generation costs for IGCC technology make it attractive to the extent that its capacity factor increases. Due to the increase of the capacity factor the generation costs arising for these power plants begin to be competitive, to the extent that the investment costs are reduced.

For its operational characteristics, IGCC power plants compete directly with GNCC systems, and exceed it in terms of investment, operation and maintenance costs. The competition is restricted to variable costs and the availability of fuel used in IGCC systems, which may be coal, petroleum coke or a mixture of both. These fuels have greater price stability and a lower overall price than the natural gas. Thus, the most important factor for the implementation and deployment on the IGCC technology is presented in the high investment cost compared to other generation technologies, but therefore IGCC power plants have a greater efficiency and a reduced emission level compared to the GNCC systems. Moreover, achieving high performance in IGCC systems through the use of syngas involves mechanical problems and the need for a refined study for the constitution of the system components. This fact is explained, since the efficiency is directly proportional to the working temperature and high compression ratios. The fact that they operate at high temperatures and high pressures requires the use of more sophisticated materials and implementation of more complex systems, to improve the performance of the turbine.

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## REFERENCES

[1] Van den Broek, M., R. Hoefnagels, et al., 2009, “Effects of technological learning on future cost and performance of power plants with $CO_2$ capture”. *Progress in Energy and Combustion Science*, Vol. **35**, pp.457-480.

[2] Lee, J.J., Kim, Y.S., Cha, K.S., Kim, T.S., Sohn, J.L., Joo, Y.J., 2009, “Influence of system integration options on the performance of an integrated gasification combined cycle power plant”. *Applied Energy*, Vol. **86**, pp. 1788–1796.

[3] Rieger, M., Pardemann, R., Rauchfub, H., Meyer, B., 2008, “Effects of ASU integration on IGCC performance and gas turbine operation”. *VGB Power Tech*, Vol. **5**, pp. 102–107.

[4] Dennis, R.A., Shelton,W.W., Le, P., 2007, “Development of baseline performance values for turbines in existing IGCC applications”. *Proceedings of ASME Turbo Expo 2007*, GT2007-28096, Montreal, Canada.

[5] Kim, Y.S., Lee, J.J., Kim, T.S., Sohn, J.L., Joo, Y.J., 2010, “Performance analysis of a syngas-fed gas turbine considering the operating limitations of its components”. *Applied Energy*, Vol. **87**, pp. 1602-1611.

[6] ALSTOM Power Turbo-Systems, 2003, “Termobahia GT24 plant: Helping Brazil reduce its reliance on rain”. *Modern Power Systems*. pp. 41-45.

[7] ARRIETA, F. R. P., 2006, “Thermal scheme simulation of thermal power plants for parametric studies preliminary performance monitoring and diagnosis”, *Ph.D. thesis in mechanical engineering*, Federal University of Itajubá, Brazil.

[8] Franco A.; and Diaz A., 2009, “The future challenges for clean coal technologies: Joining efficiency increase and pollutant emission control”, *Energy*, Vol. **34**, pp. 348–354.

[9] CIENTEC, Science and Technology Foundation, 2008, “Database for coal, biomass and waste”, [cited 2010-03-15] Available from Internet: <URL: http://www.cientec.rs.gov.br/>.

[10] Santos, A. R., 2007, “Generation of petroleum coke in the refine of heavy oils and its use in rotary kilns of clinker production”, *Ph.D. thesis in mechanical engineering*, Federal University of Itajubá, Brazil.

[11] De Souza Santos, M., 2007, “A new version of CSFB comprehensive simulator for fluidised bed equipment”. *Fuel*, Vol. **86**, pp. 1684–1709.

[12] GateCycle™, 2003, “Getting started v.5.51 and GateCycle for Windows Training Seminar Notes”. General Electric Power Systems.

[13] Sanz W., Mayr M., Jericha H., 2010, “Thermodynamic and economic evaluation of an IGCC plant based on the graz cycle for $CO_2$ capture”. *Proceedings of ASME Turbo Expo 2010*, GT2010- 22189, Glasgow, UK.

[14] Peters M.S., Timmerhaus K.D., 2001, “Plant Design and Economics for Chemical Engineers”, 4TH edition, Mcgraw-Hill, Boston, USA.

[15] DOE/NETL, 2007, “Cost and Performance Baseline for Fossil Energy Plants”, Vol. **1**, DOE/NETL-2007/1281, IGCC-Shell-051507.

[16] Bejan, A., Tsatsaronis, G., Moran M., 1995, “Thermal Desing and Optimization”, Ed. Jonh Wiley & Sons, New York, USA.

[17] EPRI - Electric Power Research Institute, 2006. “Feasibility Study for an Integrated Gasification Combined Cycle Facility at a Texas Site”.

[18] Central Bank of Brazil, 2009, “Annual Report”, [cited 2010-10-30] Available from Internet: <URL: http://www.bcb.gov.br/>

[19] Energy Research Company (Empresa de Pesquisa Energética – EPE), 2009, “Fuel Prices for Variable Cost Per Unit Calculation in Thermoelectric Power Generation”, EPE-DEE-IT-006/2009, [cited 2010-11-02] Available from Internet: <URL: http://www.epe.gov.br/>