TESTING OF A 30 kWe STATIONARY RECIPROCATING ENGINE IN DIFFERENT OPERATIONAL LOADS – PERSPECTIVE OF THE MICROCOGENERATION USING NATURAL GAS

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Abstract. *The rationing of electricity that occurred in Brazil in 2001/2002 caused an increase on the research of distributed energy generation, including cogeneration using natural gas. In order to optimize the plant operation, it is very important to evaluate the behavior of the equipments when working in a specific operational load and ambient temperature. This paper presents the analysis of the testing carried out in a 30 kWe electrical generator coupled with of a reciprocating engine fueled by natural gas, and placed in an acoustically isolated container. Temperatures of water and air were collected in the entrance of the radiator cooling system and in the air feeding system of the engine and in the exhaust pipe. Also, the followind data were acquired: the ambient temperature, airflow rate, natural gas consumption, voltage, current; reactive, apparent and active power . Thermography data were obtained using an infrared camera. Tests on the engine were carried out in five operational conditions: no load; partial reactive load, partial active load, unbalanced partial reactive load; and full reactive load. The reciprocating engine presented an efficiency of 36% and 33% when working in full reactive and partial reactive loads respectively.*

Keywords*: cogeneration, reciprocating engine, distributed generation*

1. Introduction

The crisis of energy supply, occurred in Brazil in 2001/2002, resulted of the scarcity of water on the hydropower plants reservoirs due to drought. The Brazilian electrical system is strongly dependent on the hydropower, hence, with the reduction of water to generate electricity, an emergency plan had to be enforced. Since 2003, the amount of water in the reservoirs has been reestablished to their normal condition. However, the shortage of water has showed the vulnerability of the Brazilian electrical system in relying only on one source of energy.

The lack of a long-term electricity plan, to guarantee the Brazilian energy supply, indicates that there is a serious risk to the energy shortage to occur over and over again Jannuzzi (2001)

In the 80´s, there was an increase of energy consumption of one and a half times the GNP (Gross National Product). In the 90´s the increase was two and a half times the GNP. Every year, increased the necessity to generate more electricity to sustain the energy demand and the local economy Jannuzzi (2001)

In the past years, the electric energy demand has trespassed the traditional mark of 90% of the installed capacity. The demand has reached the 98% mark in some occasions along the year. This increases enormously the chance of a blackout to occur. These are unquestionable indicators of a serious problem to come. Jannuzzi (2001)

In the middle 90´s, there was a huge modification in the Brazilian electrical sector model, the major concessionaires of electricity were privatized, and a new set of policies were created aiming the competition among the concessionaires and the attraction of investors. A regulatory agency, ANEEL, was created and rules were established to enforce investment on energy quality and efficiency, scientific research and technological development. Jannuzzi (2001)

During the 2001/2002 crisis the Brazilian Government made several incentives for the thermoelectric generation. Several thermoelectric power plants were built in the Northeast as almost all hydro electric potential has been exploited. The thermoelectric power plants run on diesel and/or natural gas. Their construction was planned in such a way that the residual heat could be used as a source of thermal energy in heat recovery units of cogeneration plants. Additionally, the government created a program called PROINFA (Project to the Incentive the use of Alternative Sources of Electricity) in which the Government guaranteed the purchase of all electricity generated through Eletrobrás (Centrais Elétricas Brasileiras).

Some researchers such as Pires, 2004, believe that a new energy crisis will occur in 2006 or 2007 as the Brazilian economy continues to grow.

The Brazilian Government through some of its agencies and enterprises has financed research on microcogeneration. Through this program, the Federal University of Pernambuco installed a microcogeneration plant consisting of a reciprocating engine of 30 kWe, a microturbine of 30 kWe, an absorption chiller of 35 kW, a compression air conditioning system of 10 kW, thermal reservoirs, thermal chambers and auxiliary equipment. The description and discussion of the plant are in Magnani et al. (2004a), Magnani et al. (2004b), Magnani (2003), Dutra (2003a) and Dutra (2003b).

The present work aims the experimental testing of the reciprocating engine generator. The thermal behavior of the plant is strongly dependent on the temperature on the site. In the Northeastern coastal area of Brazil, temperatures ranges between 28˚C and 32˚C, thus, the need for refrigeration is bigger than for heating. The temperature variation between day/night and summer/winter is small. These characteristics are important when choosing the engines for cogeneration.

The reciprocating engine was tested on three distinct loads: no load, partial load and total load. Tests were also performed misbalancing the electrical load and composing inductive/resistive loads. The results were analyzed in order to use the engine in micro cogeneration plants.

2. Equipment and instrumentation

Generator group. During the 2001/2002 electricity crisis, Leon Heimer ,one of the major Brazilian stationary engine assembler, began the production of a 30 kW micro generation group. The chosen fuel was the natural gas (NG) because of a huge NG supply contract between Bolivia and Brazil.. Due to this take-or-pay contract, the Brazilian government planned a series of actions to increase the NG consumption. The equipment was designed to work in any kind of load, varying from partial to full load in a distributed energy generation grid. It would work for small residential consumers grouped in condominiums, small shops or small commercial centers. The group generator resulted of an assembly of an American engine (PSI) and Brazilian control module, electrical generator (Negrini) and noise insulator chamber. The investment cost was below US$/kW 450.00. This type of reciprocating engine was used in Brazil in utility vehicles and it was converted by the American manufacturer to be a stationary engine using natural gas as fuel. In the present configuration, the tested engine was not equipped with a device that permitted its electrical connection with the grid. All tests were done with the engine not connected to the grid..

The generator group was designed to work for 8000 hours per year, the remaining time is scheduled for inspection and maintenance. The engine operated at 1800 rpm to increase its lifespan and to decrease its maintenance downtime. Originally, this engine was designed to work in vehicles at the optimum rotation of 3000 rpm. As the rotation decreased so did the maximum power. It was less than 50% of the nominal power. The noiseless chamber should reduce the noise to acceptable levels (75 dB at 7 m and 85 dB at 1.5 m), but, this was not measured during the test. If this proven to be true, this engine could be used in residential condominiums and small commercial shopping centers.

The reciprocating engine was an Otto Cycle, 4.3 L, six cylinders. The cylinders are set in a 90^o V configuration. The engine is a GM powertrain brand and it was produced by Power Solutions, Inc. (PSI). The engine has a 7.3 liters cooling water system. The compression ratio of the engine was 9.4:1. The valve system was hydraulically activated. Its nominal gas consumption was 11.8 m³/h at 1800 rpm, when the nominal power was 44.8 kW.

The generator group consisted of a Negrini electrical generator, model MI-200 V1.0. The electrical generator has a brushless excitation system. This kind of system yields low noise levels, simpler tension regulation system and greater durability. The tension generated by the rotating excitatory system is rectified by a tri-phase diode bridge. The electrical generator was designed to work at full-load with a power factor ranging between 0.8 and 1.0. It has 4 poles e 12 terminals, isolation class "H". The nominal tension is 380 V in a three-phase configuration; the nominal power is 37 kVa or 30 kW.

Data acquisition system. For testing the thermal and electrical behavior of the engine, it was used a National Instruments system connected to a software designed on the LabView platform. The National Instrument computer was of the model PXI, an industrial computer capable to stand relatively high extreme conditions. The computer used a NI 4351 voltimeter/thermocouple meter coupled to a TBX-68 wire borne board. The developed software was able to acquire data from seven thermocouples, two hygrometers (four wires configuration) and a calibrated flux meter based on a low cost automobile anemometer used commonly on the injection system (also mounted in a four wires configuration). Those data were acquired every 8 seconds and recorded in a text file. The National Instruments computer was connected to a flue gas analyzer, one hot wire anemometer in the engine air aspiration, an infrared camera, one analyzer of electrical energy, one balometer and the gas consumption recorder..

Thermocouples. The thermocouples used were type T (copper-constantan) covered with PVC so it could stand up to 105^{o}C. Only the thermocouple installed on the flue gases exhaust was covered with fiberglass, so it could stand up to 560^{o}C. The thermocouples were placed at 5 mm of the superior surface of the cylinder. Together with the thermocouples it was placed a glass thermometer calibrated in the range 0 ^{o}C a 400 ^{o}C. The cylinder was filled with sand. The whole assembly was put inside a furnace and the temperature measurements were done at 59 ^{o}C, 92 ^{o}C, 146 ^{o}C and 195 ^{o}C. The high thermal capacity of the sand enabled to open the furnace to take readings of the thermometer.

Table 1 and figure 1 present the place where the thermocouples where installed in the generator group. The energy balance was performed using the temperature values, the fuel flux and the air measurements obtained during the engine tests..

Table 1 – Thermocouples positioning

Therm.	Site
1	Air entrance grid in the chamber
2	Water entrance in the radiator
3	Air entrance through the radiator
4	Air entrance tube in the engine
5	Air exit from the radiator
6	Water exit from the radiator
7	Flue gas exhaust

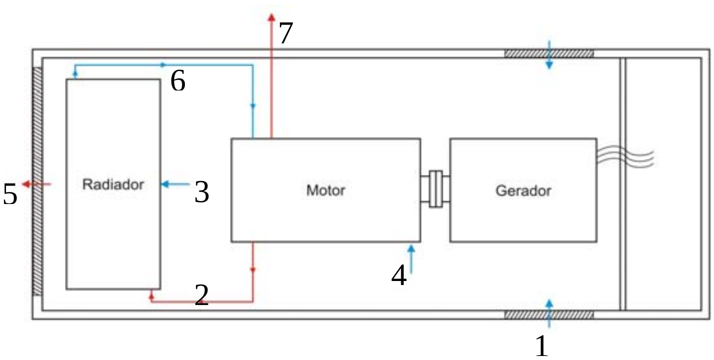


Figura 1 – Thermocouples Locations.

Flue gas analyzer. It was used an Eurotron Ecoline 6000 to analyze on-line the flue gas at the exhaust pipe. The gas analyzer consists of two probes. The first probe directed the gas to the three electrochemical cells (one for oxygen, one for CO and another for NO). The second one had the temperature and humidity sensors. Additionally, this equipment can perform NOx calculations. It was used a T-type thermocouple which could work in the range 0 to 999,9 ^{o}C, with resolution of 0,1 ^{o}C and precision of ± 0,3%.

Natural gas consumption. For measuring the NG flow rate, it was used the integrated value of the gas meter divided by the time interval between measurements (commonly 5 minutes). There are temperature and pressure indicators in the gas station that supplies the NG for the cogeneration plant. Using values of volumetric flux, temperature and pressure data, the flow rate was transformed in mass rate (in kg/s) using the perfect gas equation.

Air flow in the engine entrance. For measuring the air flux entering the engine, it was used a specially developed by (LMPT: Laboratório de Meios Porosos e Propriedades Termofísicas dos Materiais – UFSC), a low cost meter based on a commercially available hot wire anemometer, commonly used in vehicles. The anemometer was built-up inside a conic tube adjusted to the suction of the engine. An electronic board converted the signal from the anemometer to a 4 to 9 V signal. The voltage signal is converted to kg/s using a supplied calibration curve which is dependent on the air temperature.

Airflow through the radiator. It was used a balometer Prohood with a bell hood built by AIRFLOW. This equipment has the advantage of having a large cross sectional area that provokes a low head loss and a large number of velocity sensors.

Infrared Camera. For the qualitative thermal analysis of the system, it was used an Infrared Camera brand FLIR model S45. Its resolution is 0.08 ^{o}C and its precision is ± 2 ^{o}C.

Electrical energy analyzer. On the electrical cable, it was mounted an energy analyzer brand Embrasul model RE6000. This device enables to measure and to log the following variables: voltage, current, frequency, active power, reactive power, apparent power, power factor, tension harmonics and current harmonics. The analyzer works in the range 0 V to 600 V and 0 to 300 A.

3. Methodology and Tests

For the analysis of the thermal and electrical behavior of the generator group, it was designed two sets of tests. In the first one, the generator group would generate energy to be dissipated in a balanced resistive bank of maximal 35 kW (all the phases have the same current). In this balanced way the group was tested with no load, partial load and full load. In each case the motor ran during 30 minutes.

In the second set of tests, consisted of two tests. The goal was to verify the quality of electrical energy generated, when operating under unbalanced loads (distinct currents in each phase) or, in a mix of resistive and inductive loads. In the first test, there were two phases with resistive load and the third phase with no load. In the second one, the three phases were working plugged on a balanced resistive with partial load and an electrical engine of 3 HP working without load (generating an inductive load). Most of the testing time were carried out with the generator group working with the doors of the noiseless chamber closed. Only when performing the thermal scan that the doors were open.

4. Results

The thermal power to cool the engine was calculated using the values of air flux through the radiator (measured by the balometer) and the temperature difference between the temperatures of the air intake and air exit from the noiseless chamber using equation 1. This same variable was calculated using the global energy balance of the engine. It was found differences between those values. In accordance with Ceviz and Kaymaz (2005) and Bidini, et al. (1998), our results showed that those differences were caused by the heat transfer between the walls of the chamber. Although those losses were not measured in this work, a qualitative analysis of these losses was done using the thermographical analyses. Figure 2.a shows a thermography picture of the front end of the chamber. Analyzing this thermogram, it was possible to notice the high temperature in the wall where there was the internal metallic structure of the chamber. The other places were well insulated and the temperatures were smaller.

$$\dot{Q}_{Cooling} = \dot{m}_{bal} . c_{p,air} . (T_{exit\_radiator} - T_{amb}) \qquad \text{Eq. (1)}$$

$$\dot{Q}_{Cooling} = \dot{m}_{bal} . c_{p,air} . (T_{exit\_radiator} - T_{int\_radiator}) \qquad \text{Eq. (2)}$$

where:

$\dot{Q}_{Cooling}$ = the energy carried by the air as it cools the engine and radiator

$\dot{m}_{bal}$ = the mass flux of air

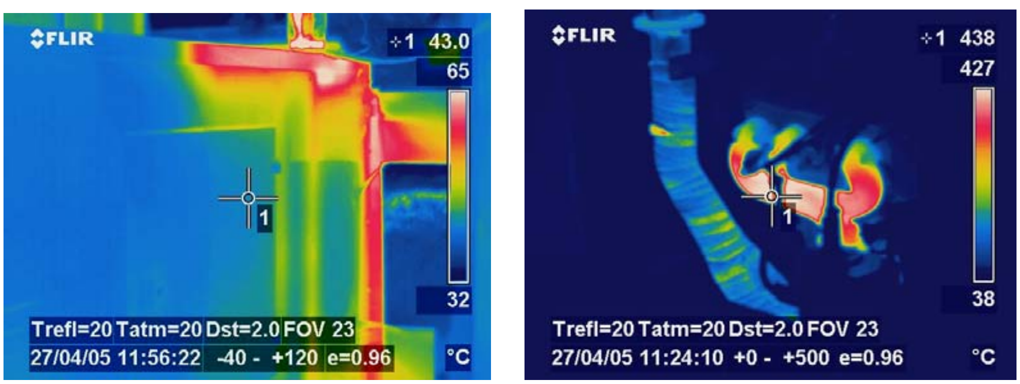
$c_{p,air}$ = the specific heat of the air

$T_{exit\_radiator}$ = the temperature of the air exiting the radiator

$T_{int\_radiator}$ = the temperature of the air in the intake of the radiator

T_{amb} = the temperature of the air entering the chamber

The total cooling power in the engine is the sum of the heat loss through the wall and the heat carried by the air (water cooling energy and the heat transfer between the air and the block). Figure 2.b shows the high temperature of the engine inside the chamber. This is the source of the heat transfer between the block and the air. The water cooling, calculated by Eq. (2), is extremely important to the engine and the oil. The cooling water reached 70 ºC when working on maximum load, and returns to the block at 40 ºC. This energy corresponds roughly to 1/3 of the energy supplied by the fuel. Although this heat was not used for cogeneration, it is an important source of thermal energy.



(a) (b)

Figure 2 – Thermography of: (a) the external chamber wall and (b) the engine block and exhaust tube.

Table 2 shows the calculations done using the measurements data. It is possible to notice the energy of the water cooling is, in each case, roughly half the energy carried by the air. Another important information is the error on the energy balance shown on table 2. In the full load, the largest error was obtained. In the time of the publication of this work it was not possible to determine the source of this error.

Table 2 – Results of the testing on the engine

		No load	Partial balanced resistive load	Full balanced resistive load	Partial resistive load on two phases and no load on the third	Partial resistive inductive load on the three phases
$\overset{o}{Q}_{cooling}$	kW	26,1417	32,5466	36,5312	29,4090	31,3348
$\overset{o}{Q}_{water,cooling}$	kW	15,4722	19,0783	21,1482	17,5313	18,8047
$\overset{o}{E}_{fuel}$	kW	25,9225	57,2792	91,3556	42,6100	58,7387
$\overset{o}{E}_{exhaust}$	kW	3,2874	5,4805	7,1696	4,8422	5,6798
$\overset{o}{E}_{air\_\mathrm{int}}$	kW	0,1070	0,1537	0,1830	0,1327	0,1506
η_{group}	%	0,00%	23,14%	29,13%	16,59%	23,46%
P_{phaseA}	kW	0,000	4,424	8,839	0,000	4,577
P_{phaseB}	kW	0,000	4,389	8,861	3,656	4,578
P_{phaseC}	kW	0,000	4,445	8,917	3,419	4,632
P_{ele} (total)	kW	0,000	13,255	26,610	7,069	13,782
P reactive	kVA	0,000	0,648	1,475	0,448	2,072
Energy error	kW	-3,40	6,15	21,23	1,42	8,09

The high heat value can be calculated by chromatogram of natural gas.

The high quality, high temperature thermal energy yielded by the chimney is roughly 5-10% of the chemical energy of the fuel. This energy is very useful to residential cogeneration plants (Onovwiona and Ugursal (2004).

The group thermal efficiency was calculated using equation 3. It was possible to notice the influence of the total load on the efficiency. As the load increases so did the thermal efficiency. Moss, Roskilly and Nanda (2005) present the value of 35% as the characteristic value for stationary reciprocating engines. According to Kanoglu, Isık and Abusoglu (2005), another factor to influence negatively the efficiency was the air temperature during the essays (32 ^{o}C to 40 ^{o}C). These differences are usual in tropical coastal climates.

$$\eta_{group} = \frac{\overset{o}{P}_{ele}}{\overset{o}{E}_{fuel}} \qquad \text{Eq. (3)}$$

where:

$\overset{o}{E}_{fuel}$. = chemical energy of the fuel convert in thermal energy through the combustion

$\overset{o}{P}_{ele}$ = electrical energy conducted by the cables

η_{group} = thermal efficiency of the group

Two major drawbacks were identified during the testing: the temperatures of the air entering the chamber and of the exhaust gases. The temperature of the air entering the chamber is lower than the temperature of the air entering the aspiration tube of the engine. This is highly expected as the air enters in contact with the block and the generator inside the chamber. This increasing of the temperature causes the increase of the specific volume of the air. Consequently, the mass flux of air (and the power of the engine) decreased. The increase of temperature acts also on the efficiency of the engine, although the influence is no as strong as in the case of the microturbine.

The other disadvantage does not act directly on the engine behavior but decrease the prospects of cogeneration use. The temperature of the exhaust gases is higher at the exhaust manifold of the engine than in the chimney. This can be seen in figure 2.b as a high temperature place over the engine. This non-insulated region is a major source of high thermal energy that could be used in cogeneration using the flue gases heat. Although this energy could be used with a simple insulation of the flue gas manifold, extreme care must be taken to verify if the engine can withstand the heat.

For the engine working with no load, the emission of NO were very low (72 ppm), increasing to 500 ppm to a partial load and 1200 ppm for the full load. The production of NOx is function of the temperature and the design of the engine (Kesgin, 2003). The excess oxygen was kept constant (10%) for the engine working with no load or partial load. When working n full load, the excess oxygen decreased to 8%. During the warming up of the engine, working with no load, the CO production reached 3000 ppm. As the engine reached its nominal operating temperature, the CO emission reduced to 200-300 ppm. It seemed to have no dependency on load. The CO_2 emission remained constant 5-6% during all the tests.

During the tests using balanced loads (all the phases with the same current) it was not observed significant variations on the quality of the electrical energy. Nevertheless in the unbalanced tests the voltage presented a large variation between the phases: 228 V, 216 V and 227 V.

5. Conclusion

Stationary reciprocating engines can be used in the Brazilian northeast due to its lower cost when compared with microturbines. It is proposed some changes in the project of this specific engine: to move the aspiration tube to the outside of the chamber and to insulate the flue exhaust manifold. Preliminary results show the air flux in the radiator is very high to this engine. Decreasing the power of the fan, could increase the delivered power.

The problem of the variation of the voltage in the phases when the group is submitted to an unbalanced load must be carefully taken into account.

The efficiency of the engine was found to be the characteristic for stationary Otto engines (near 35% for full load). The flue gas heat (10%) and the cooling water system energy (20% for full load) should be strongly considered for cogeneration. For the studied cogeneration plant this is not possible because the absorption chiller requires higher temperatures (90 ^oC) than the cooling water (70 ^oC).

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7. References

Al-Sarkhi, A., Jaber, J.O., Abu-Qudais, M., Probert, S.D., 2005, “Effects of friction and temperature-dependent specific-heat of the working fluid on the performance of a Diesel-engine”, Applied Energy, Vol. xxx , pp. xxx–xxx (in press)

Bidini, G., Desideri, U., Saetta, S., Bocchini, P. P., 1998, “Internal combustion engine combined heat and power plants: case study of the university of perugia power plant”, Applied Thermal Engineering, Vol. 18, pp. 401-412

Bidini, G., Grimaldi, C.N., Mariani, F., 2000, “Experimental analysis of the actual behaviour of a natural gas fueled engine Caterpillar (CAT)-3516”, Applied Thermal Engineering Vol. 20, pp. 455-470

Ceviz, M.A., Kaymaz, I.,2005, “Temperature and air–fuel ratio dependent specific heat ratio functions for lean burned and unburned mixture”, Energy Conversion and Management, Vol. Xxx, pp. xxx–xxx (in press)

Dutra, J. C. C. ; Primo, A. R. M. ; Magnani, F. S. ; Guerrero, J. R. H. ; Anselmo Filho, P. ; Melo, N. R. ; Soares, R. R. E. ., 2003a, Technical And Economic Study Of Micro-Cogeneration In Residential Scale: A Case Study. In: 17th Edition Of The International Congress Of Mechanical Engineering, 2003, São Paulo. 17th Edition Of The International Congress Of Mechanical Engineering.

Dutra, J. C. C. ; Primo, A. R. M. ; Magnani, F. S. ; Guerrero, J. R. H. ; Anselmo Filho, P. ; Melo, N. R. ; Soares, R. R. E. , 2003b, “Estudo Técnico E Econômico De Micro-Cogeração Em Escala Residencial:

Estudo De Caso". In: Vi Congresso Ibero-Americano De Engenharia Mecânica Cibem6, Coimbra. Anais Do Vi Congresso Ibero-Americano De Engenharia Mecânica Cibem6.

Kesgin, Ugur, 2003, "Study on prediction of the effects of design and operating parameters on NOx emissions from a leanburn natural gas engine", Energy Conversion and Management, Vol. 44, pp. 907–921

Kanoglu, M., Isık, S. K., Abusoglu, A., 2005, "Performance characteristics of a Diesel engine power plant", Energy Conversion and Management, Vol. 46, pp. 1692–1702

Magnani, F. S. ; Melo, N. R., 2004a, "Análise De Sistemas De Micro Cogeração Operando Com Cargas Elétricas E Térmicas Variáveis". Conem, 2004, Belém. Anais Do Conem, 2004. V. 1. P. 1-10.

Magnani, F. S. ; Melo, N. R., 2004b, "Análise Do Modo De Operação De Sistemas De Micro-Cogeração Em Casos Em Que As Tarifas Ou Demandas Reais São Diferentes Das Usadas Durante O Dimensionamento Do Sistema." Xxv Cilamce - Iberian Latin American Congress On Computational Methods, Recife. Proceedings Of The Xxv Cilamce - Iberian Latin American Congress On Computational Methods, 2004. V. 1. P. 1-19.

Magnani, F. S. ; Usui, T. ; Primo, A. R. M., Guerrero, J. R. H. ; Dutra, J. C. C., 2003, "Financial Optimization Of Micro Cogeneration Plants Using A Task Configuration System." 17th Edition Of The International Congress Of Mechanical Engineering, 2003, São Paulo. 17th Edition Of The International Congress Of Mechanical Engineering.

Moss, R.W., Roskilly, A.P., Nanda, S.K., 2005, "Reciprocating Joule-cycle engine for domestic CHP systems", Applied Energy, Vol. 80, pp. 169–185

Onovwiona, H.I., Ugursal, V.I., 2004, "Residential cogeneration systems: review of the current technology", Renewable and Sustainable Energy Reviews, Vol. Xx, pp. 1–43

Pires, Adriano - diretor do Centro Brasileiro de Infra-Estrutura (CBIE) "Alertas sobre crise tentam influenciar votação de MP hoje. Investidores pressionam por mudanças no modelo elétrico", Jornal do Commércio, 17/02/04.

Jannuzzi, Gilberto De Martino – "Planejando a Crise de Energia Elétrica" Revista Economia e Energia núm. 20 de maio de 2001