THERMOECONOMIC ANALYSIS OF A CAES PLANT (COMPRESSED AIR ENERGY STORAGE) - SIMULATION WITH DATA FROM A BRAZILIAN ELECTRIC POWER SUPPLIER

Francisco de Sousa Júnior
Universidade Federal de Itajubá – Departamento de Mecânica
Av. BPS, 1303 – Itajubá, MG – CEP.: 37500 000
xico@iem.efei.br

Rogério José da Silva
Universidade Federal de Itajubá – Departamento de Mecânica
Av. BPS, 1303 – Itajubá, MG – CEP.: 37500 000
rogério@iem.efei.br

Abstract. *One of the existent alternatives for the electric power generation in peak-load demand is that corresponding to the use of gas turbines endowed with an underground reservoir air system. In this work, a thermoeconomic analysis is conducted, based on the theory developed by Valero et all (1986, 1987, 1993) of a CAES plant (Compressed Air Energy Storage) through the simulation with data of from a Brazilian Electric Power Supplies. That theory allows evaluating the costs of each stage of the process of the installation that contributes to the formation of the final cost of the electric power generated. Besides identifying the processes or subsystems of the plant where there is a larger generation of costs and losses, it was concluded that the final generated electric unitary power cost can be obtained with larger precision once the detailed monetary costs involved in each stage of the plant are known. This cost can then be compared with the values practiced by the market, verifying or not its economical feasibility.*

Keywords. CAES Plant, thermoeconomic analysis, exergy, exergoeconomic costs, economical feasibility.

1. Introduction

One of the existent alternatives for the electric power generation in peak-load demand is that corresponding to the use of gas turbines endowed with an underground reservoir air system. This system is a modification of the conventional gas turbine plants. The process consists basically in storing compressed air in an underground reservoir in off-peak load demand, using for that a chain of compressors of smaller load, and in the peak load demand withdraws this air, heating it, feeding it in a combustion chamber and expanding the gas in a gas turbine chain generating electric energy for the grid. The compression cycles and expansion are independent. The objective of this work is to conduct a thermoeconomic analysis based on the theory developed by Valero et all (1986, 1987, 1993) of a CAES (Compressed Air Energy Storage) Plant through the simulation with data from a Brazilian Electric Power Supplier. That theory allows us to evaluate the costs of each stage of the plant process that contribute to the formation of the final cost of the electric energy generated.

We concluded that, besides identifying the process or subsystems of the plant where there is a larger generation of costs, if the detailed monetary costs involved in each stage of the plant is well-known, the final unitary cost of the electric energy generated can be obtained with a larger precision, and then, compared with the values practiced by the market, verifying or not its economical feasibility.

2. How a CAES Plant Works

The theoretical basis associated with the thermodynamic cycle for a CAES generating facility is that of the simple gas turbine cycle. However, unlike a conventional gas turbine plant in which the net shaft power is reduced by two thirds due to the power required to drive the air compressor, in a CAES generating plant the air compressor and turbine are each independently connected to the motor/generator by clutches and the power produced by the turbine is available for transfer to the electrical grid. During off-peak demand, when excess power is available on the grid, the CAES is in the charging mode and the motor/generator works as the power unit to run the plant's air compressor to charge up the air storage reservoir (see Figure 1).

During periods of peak-load demand, the plant extracts compressed air from the storage reservoir, passes it to a recuperator, to a combustion chamber and directs it to the turbines chain. A recuperator heats the air employing the output turbine gases. The heated air mixed with fuel and the subsequent combustion process drive the motor/generator to produce extra power for delivery via the electrical grid. This relieves the turbine of the excess load required to drive the air compressor, resulting in the CAES generation plant having an increased net output of two to three times that of the simple-cycle gas turbine, with the same output power.

3. Thermoeconomic Analysis

The McIntosh CAES Plant (Alabama, USA), as shown in Fig. (1), is analyzed with the thermoeconomic theory developed by Valero et all (1986, 1987, 1993). With that method it is possible to obtain the amount of necessary exergy to the unitary energy generation, as well as of its intermediate stages. If it's known the monetary costs involved in each stage of the plant it will be possible to obtain the unitary end cost of the exit energy, and then compare it with the price practiced by the market. So, the exergetic and exergoeconomic costs are calculated involving in the main stages of the CAES Plant.

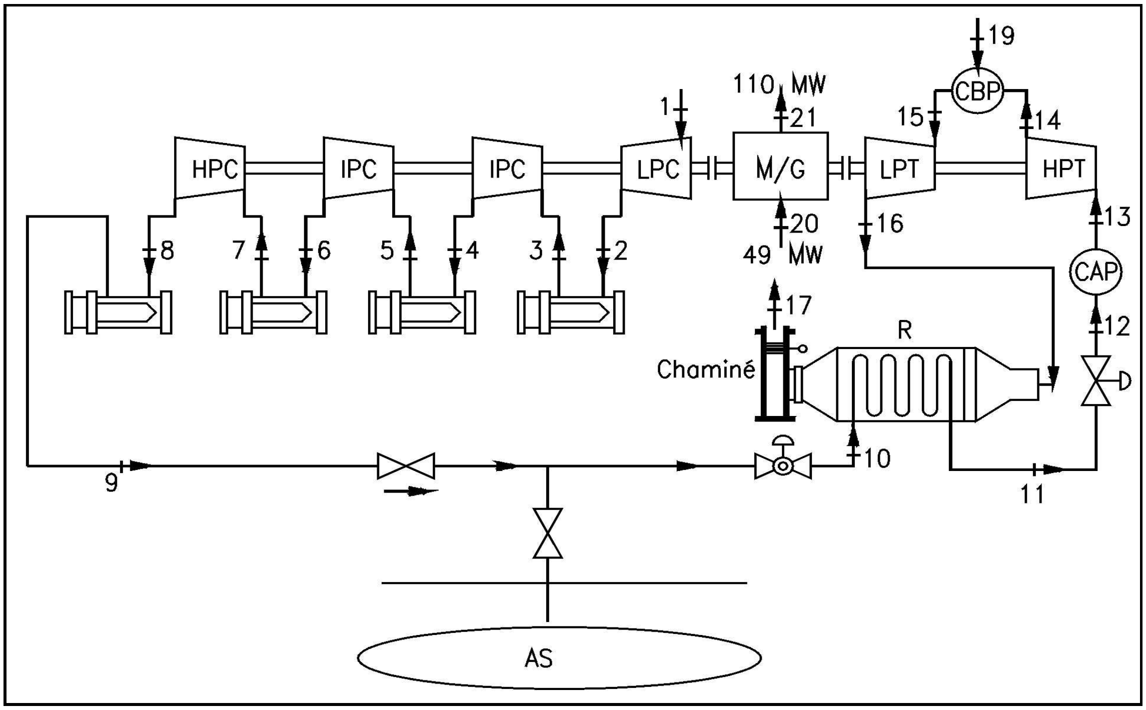

Figure 1. Outline of McIntosh CAES Plant (United States)

Table (1) presents the temperature, pressure, enthalpy and entropy values for the gas from the point 1 to the 17, as indicated in Fig. (1).

Table 1. Pressure, temperature, enthalpy and entropy values for the current gas of the USA CAES Plant

Point	Temperature [K]	Pressure [bar]	Enthalpy [kJ/kg]	Entropy [kJ/kgK]
1	298,00	1,034	298,97	6,6998
2	489,31	4,137	493,06	6,7981
3	308,00	4,137	309,09	6,3289
4	425,20	11,032	427,52	6,3728
5	309,09	11,032	309,09	6,0472
6	419,77	28,269	422,00	6,0895
7	309,09	28,270	309,09	5,7769
8	424,16	74,000	426,46	5,8237
9	321,80	74,000	322,97	5,5446
10	308,00	48,954	309,09	5,6192
11	558,50	47,920	564,66	6,2313
12	558,50	43,900	564,66	6,2564
13	810,80	42,749	834,58	6,6646
14	655,20	15,440	666,28	6,7279
15	1144,00	15,169	1212,14	7,4830
16	644,10	1,034	654,89	7,4830
17	558,50	1,034	-	-

There is no need to calculate the enthalpy and entropy values at point 17, because the residual heat of the gas that leaves the recuperator doesn't have any use, being discharged directly by the chimney.

3.1. Thermoeconomic Theory

An industrial productive process can be considered as a system of several units (equipment and machines) related to each other through materials and energy flows or changed information. The CAES Plant can also be considered as a system, which consists of a series of stages, i.e., air compression, cooling, storage, heating (recuperator), combustion and expansion for the electric power generation. All these stages carry out their own functions, allowing a peculiar analysis of its function inside of the global process of energy generation.

The exergy, as a state function (once defined the environmental conditions), reflects the minimum amount of work done to obtain a product starting from the reference atmosphere. Thus, it can be said that the exergy is independent of the used process for the production of a product and it represents a minimum cost (in energetic terms) necessary for obtaining this product. Since all actual processes are irreversible, once exergy destruction or loss occurs, the necessary exergy needed to obtain a functional product, denominated here as a exergetic cost $\left(B^*\right)$, will always be a function of the used process, incorporating the exergetic losses of the process, and, whatever the process is, the exergetic cost will always be larger than the exergy (Lozano and Valero, 1987). So:

$$Exergetic\,Cost > Exergy$$

So, the energetic optimization process should progress in the sense of maximizing the exergetic global value "η" and of minimizing the value of the exergetic unitary cost "k", whose definitions are presented below:

$$\eta_B = \frac{Exergy}{Exergetic\,Cost} \tag{1}$$

$$k = \frac{Exergetic\,Cost}{Exergy} \tag{2}$$

For the exergetic cost estimate $\left(B^*\right)$ in a system, it is necessary, initially, to define the heat, work or matter flows, in the control volumes, represented by the solid materials, gases or energy flows, defining those that act as exergy sources (or fuels), denominated as "FUEL" (F), necessary to manufacture a certain "PRODUCT" (P) by the system. So, the exergy contained in a product obtained from an analyzed system, will be given by:

$$\mathrm{Pr}\,oduct\left(P\right) = FUEL\left(F\right) - LOSSES\left(L\right) - DESTRUCTION\left(D\right) \tag{3}$$

The process global efficiency $\left(\eta_B\right)$ in the system can be evaluated for the follow relation:

$$\eta_B = \frac{PRODUCT\left(P\right)}{FUEL\left(F\right)} \tag{4}$$

The inverse of the exergetic efficiency represents the consumption exergy requested by an installation to obtain the product, represented by the unitary exergetic cost $\left(k\right)$, which can be calculated by the relationship between:

$$k = \frac{1}{\eta_B} = \frac{FUEL\left(F\right)}{PRODUCT\left(P\right)} \tag{5}$$

$$k = 1 + \frac{LOSS\left(L\right) + DESTRUCTION\left(D\right)}{PRODUCT\left(P\right)} \tag{6}$$

In the CAES plant process are considered as FUEL: the exergy in the electric power form supplied to run motor/generator in the compression cycle, to the cooling water circulation bombs, to the lubrication bombs and the exergy supplied for the fuel burning in the two combustion chambers. The final electric power supplied by the two turbines is considered as a PRODUCT.

The hot gases that are emitted through the chimney for the atmosphere without any use are considered as LOSSES, and are considered null in the exergetic cost evaluation as well as the cooling water used in the heat exchanges.

3.2. Incidence Matrix and F, P e L definition

In order to conduct a thermodynamic analysis of a plant or of a process, it must previously be defined a group of equipments or subsystems, in such a way that all of them constitute the plant as a whole, and others groups of matter, heat and work flows which these link to each other and around the plant. In such way, it can be said that:

Energetic System = Subsystem or Equipments + Matters and/or Energy Flows

The relationship between the flows and subsystems is established by the Incidence Matrix A (n, m), where "n" represents the subsystems number and "m" the flows number (Valero et all, 1987).

3.3. Attribution Costs Rules

Valero et all (1986, 1987) formulated a procedure for costs attribution based only on the thermodynamics. The bases of their method are shown below:

- The exergetic cost of a Flow $\left(B^*\right)$, Fuel $\left(F^*\right)$ or Product $\left(P^*\right)$ is the real amount of exergy that has been necessary to produce it.

- A detailed analysis of the nature of the process and the definition of F-P-L allow solving the problem of costs attribution.

- The exergetic cost of the entrance flows in each equipment should be rebounded in the useful flows that leave it.

So, some basics propositions for the problem of costs attribution were defined:

PROPOSITION 1: The exergetic cost is a preservative property and, therefore, $\sum B^* = 0$.

PROPOSITION 2: For the total fuel multiple components of the subsystem, the unitary exergetic cost of the exit flows should be the same as the entrance flows.

PROPOSITION 3: If a subsystem has a total product formed by several components, then all of them will have the same exergetic cost.

PROPOSITION 4: If a component of the product has several exit flows, each of them will be attributed the same unitary exergetic cost.

PROPOSITION 5: In the absence of an external attribution for the system losses flows, it should be attributed to them a null exergetic cost, once they don't have any subsequent use.

PROPOSITION 6: In the absence of an external value, the exergetic cost of the entrance flows to the system is the same of its exergy. If the flow "j" that enters in any one of the subsystems, external to the defined border for the system, in other words, originating from the spill, or of another subsystem, then: $B_j^* = B_{j^*}$.

Considering a system constituted of several subsystems, the exergetics balance costs, based on the Proposition 1 of the (n) subsystems that constitute it, will correspond to the system of equations:

$$A\,x\,B^* = 0 \tag{7}$$

Once the flows number (m) is always larger than the subsystems number (n), the matrix "A" will need (m-n) equations to solve the problem of attribution exergetics costs to the all flows. Then, it should be determined some "α" matrix (m-n,m) and a column vector "W" (m-n,1) that satisfies the equation:

$$\alpha\,x\,B^* = W \tag{8}$$

So, the equations system necessary to calculate the exergetics costs will be given by:

$$\begin{bmatrix} A \\ \dots \\ \alpha \end{bmatrix} x\,B^* = \begin{bmatrix} 0 \\ \dots \\ W \end{bmatrix} \tag{9}$$

The matrix "α" and the column vector "W" are determined according to the attribution cost rules previous mentioned.

Defining:

$$A = \begin{bmatrix} A \\ \dots \\ \alpha \end{bmatrix} \; ; \; Y = \begin{bmatrix} -Y^* \\ \dots \\ W \end{bmatrix} \tag{10}$$

Making $Y^* = 0$, the system can be written in a more compact way so that:

$$A \, x \, B^* = Y \tag{11}$$

So, the matrix will have now dimension (m,m), having,, therefore, only one solution. Once the values of the exergy of the “m” flows are known, the resolution of the system will depend on the external attribution values of the column vector “Y”, so that the exergetic costs flows of the system can be known.

Other values can be calculated starting from the exergetic costs acquired for a given system, which are listed below (Valero et all, 1993):

- Exergetic unitary cost, given by:

$$K_i^* = \frac{B_i^*}{B_i} \tag{12}$$

- System irreversibility:

$$I_i = F_i - P_i \tag{13}$$

- Percentage irreversibility generated in the system in relation to the total FUEL introduced in the global system:

$$\delta = \frac{I_i}{F_T} \tag{14}$$

- FUEL unitary exergetic cost:

$$K_{F_i}^* = \frac{F_i^*}{F_i} \tag{15}$$

- PRODUCT unitary exergetic cost:

$$K_{P_i}^* = \frac{P_i^*}{P_i} \tag{16}$$

3.4. Exergoeconomic Costs

The calculation of the monetary costs of a system or a thermal plant for electric power generation is of great importance, mainly when these costs can be calculated in the several subsystems or equipments that constitute the system or the thermal plant.

Based on the same theory previously discussed, it still can be obtained another cost called exergoeconomic cost (Π) that represents the sum of the contributions of the several exergy flows (B) in the constitution of the monetary cost of a given product.

So, the exergetics costs (B^*) represent the amount of exergy spent to produce a certain product, and the exergoeconomic costs, the monetary costs originated in the productive process, associating in their acquirement, not just the energetic cost, but the capital, operation, maintenance, installation, etc.

According to the Valero et all (1986) theory, the matrix (m,m) previously defined for the calculation of the exergetics cost (B^*), multiplied by the column vector (Π), that represents the exergoeconomics costs that will be calculated, will be equal to the column vector (Z), that contains the external economical attributions for the matter, heat or work flows of the system analyzed. So:

$$A\,x\,\Pi = Z \quad (17)$$

Whose incognita, Π_j, are the exergoeconomics costs of the "m" flows.

$$Z = \begin{bmatrix} -Z \\ \ldots \\ w_Z \end{bmatrix} \quad (18)$$

The vector "w_Z" is the attribution express from the economical values to the entrance flows of the system or of those that exits the system that don't form the total product. But the vector "-Z" includes the capital costs, maintenance, amortizations, personal, installation, etc.

3.5. Thermoeconomic Analyses

It was carried out a simulation of the CAES Plant quoted considering the energy costs values practiced by a Brazilian Electric Power Supplier, more precisely in Minas Gerais state. So, all the relative data for the calculation of the costs will obey the tables of prices practiced by this company (CEMIG - Centrais Elétricas de Minas Gerais).

It was considered that the generation cycle would be carried out from Monday to Friday on the peak-load demand, which corresponds to 5:00 pm to the 10:00 pm (www.ons.com.br). In the compression cycle the operation would be on off-peak-load demand during 5 hours on weekdays and 48 hours on the weekends with the goal to complete the air reservoir.

Table (2) presents the operation hours simulated with the McIntosh CAES Plant in both, compression and generation cycle, for the Brazilian case.

Table 2. Hours of operation of the McIntosh CAES Plant simulated for the Brazilian case (Minas Gerais)

Quantities of operation hours (compression and generation) on weekdays [days]	**Quantities of hours in the generation cycle on weekdays [hours]**	**Quantities of hours in the compression cycle on weekdays [hours]**	**Quantities of hours in the compression cycle on weekends [hours]**
5	5	5	48

Nowadays, there are regional rates for the electric power in Brazil, with small price difference among the companies. The rates are divided in three big groups: conventional rate, Horo-Sazonal blue rate and Horo-Sazonal green rate. The thermal plant studied buys electric power inside the Horo-Sazonal blue rates being classified in the subgroup A2. The relative prices practiced by this subgroup were used in the exergoeconomic analyses.

Table (3) presents the values of Horo-Sazonal blue rate of subgroup A2.

Table 3. Values of Horo-Sazonal blue rate of subgroup A2

Schedule Segment	**Demand**			
Subgroup	**Peak**		**Off-Peak**	
A2 (88 kv to 138 kv)	12,00		2,76	
Seasonal Segment	**Consumption (R$ MWh)**			
	Peak		**Off-Peak**	
Subgroup	Dry	Humid	Dry	Humid
A2	67,30	62,78	48,23	44,22

Source: www.cemig.com.br (no. 126, of April 05, 2001).

So, taking into account the operation prices in the off-peak seasonal schedule, peak, and in the dry and humid period, it took place a rising of costs for a global analysis, being compared with the acquired costs on the different rates.

In order to accomplish the thermoeconomic analysis, the CAES Plant had its several sections and equipments grouped in such a way that the compression cycle was divided in just one subsystem, including the heat exchangers, the water and oil pumps and the auxiliary equipments. The generation cycle was divided in six subsystems: recuperator, throttle pressure valve, high-pressure combustion chamber, high-pressure turbine, low-pressure combustion chamber and low-pressure turbine.

The results of the calculations were based on the energy analysis of the compression and generation cycle, also considering that the natural gas used in the CAES Plant has a net calorific value of 45756,30 kJ/kg and a cost of 2,446 US$/GJ (www.ons.com.br).

4. Results

4.1. Compression Cycle

Figure (2) presents an outline with the physical structure of the compression cycle. The description of the flows involved in the process is presented in Tab. (4), the calculations results of exergy flows, exergetic cost and unitary exergetic cost values are presented in Tab. (5). Table (6) presents the calculations results of efficiency and costs for the compression cycle.

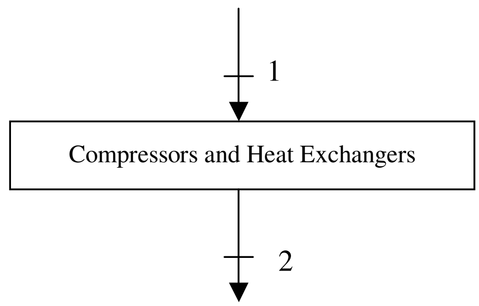

Figure 2. Outline of the compression cycle physical structure.

Table 4. Description of compression cycle flows

Flow	Flow description
1	Electric power entrance – compressors activator, water, oil and lubricant pumps, auxiliary equipments activator for the cooling motor/generator.
2	Exit of the last heat exchanger air to be stored in the air reservoir.

Table 5. Calculations results values of the exergy flows, exergetic cost and unitary exergetic cost for the compression cycle

Point	**Exergy** (B) **[MW]**	**Exergetic Cost** (B^*) **[MW]**	$K^* = B^* / B$
1	49,00	49,00	1,000
2	32,77	49,00	1,495

Table 6. Efficiency calculations and costs result in the compression cycle

VC	**FUEL (F) [MW]**	**PRODUCT (P) [MW]**	**IRREV. (I) [MW]**	η_B	**K**	δ	$K^*_{F_i}$	$K^*_{P_i}$
Compression Cycle	49,00	32,77	16,230	0,669	1,495	0,331	1,000	1,495

4.2. Generation Cycle

Figure (3) presents an outline with the physical structure of the generation cycle. The identification of the flows involved in the process is presented in Tab. (7).

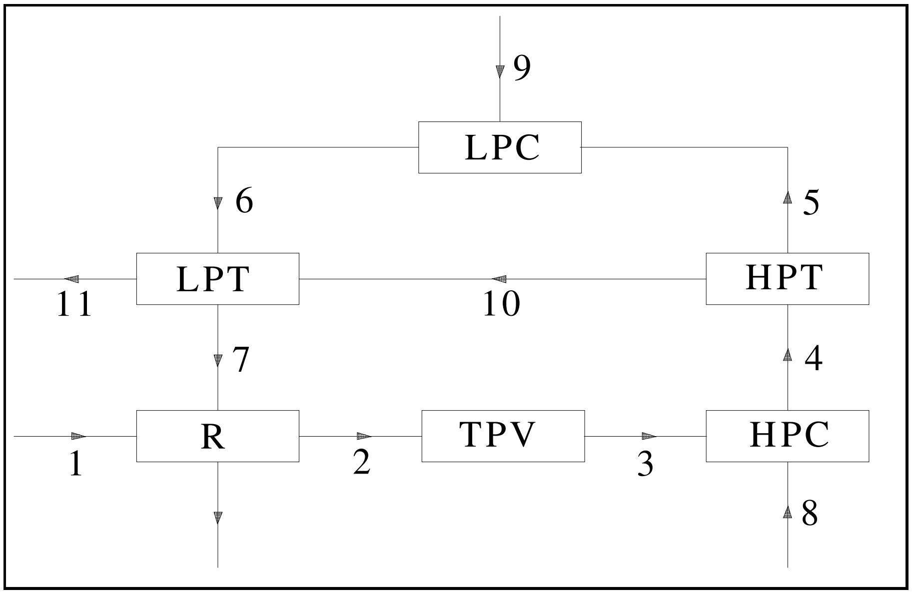

Figure 3. Outline of the physical structure of the generation cycle

Table 7. Description of the generation cycle flows

Flows	Description
1	Recuperator air entrance originating from air reservoir
2	Air exit from the recuperator and entrance in the throttle valve pressure
3	Fuel entrance of low-pressure combustion chamber
4	Gas exit from the high-pressure combustion chamber and entrance in the high-pressure gas turbine
5	Gas exit from the high-pressure gas turbine and entrance in the low-pressure combustion chamber
6	Gas exit of the low-pressure combustion chamber and entrance in the low-pressure gas turbine
7	Gas exit of the low-pressure gas turbine and entrance in the recuperador
8	Fuel entrance in the high-pressure combustion chamber
9	Fuel entrance in the low-pressure combustion chamber
10	Energy generated by the high-pressure gas turbine
11	Energy generated by the low-pressure gas turbine plus the high-pressure gas turbine

The identification of the subsystem regarding to Fig. (3) is presented in Tab. (8) below.

Table 8. Identification of the generation cycle subsystems

	Subsystem
1	Recuperator (R)
2	Throttle pressure valve (TPV)
3	High-pressure combustion chamber (HPC)
4	High-pressure gas turbine (HPT)
5	Low-pressure combustion chamber (LPC)
6	Low-pressure gas turbine (LPT)

The calculations results values of the exergy flow, exergetic cost and unitary exergetic cost are presented in Tab. (9).

Table (10) presents the calculations efficiencies results and costs for the generation cycle.

Table 9. Calculations results values of exergy flow, exergetic cost and unitary exergetic cost for the generation cycle

Point	**Exergy** (B) **[MW]**	**Exergetic cost** (B^*) **[MW]**	$K^* = B^* / B$
1	51,35	51,34	1,000
2	62,66	88,97	1,420
3	61,51	88,97	1,446
4	95,46	136,56	1,431
5	62,75	89,79	1,431
6	120,65	184,96	1,533
7	21,99	37,63	1,711
8	47,59	47,59	1,000
9	95,17	95,17	1,000
10	26,50	46,78	1,765
11	110,00	194,10	1,765

Table 10. Calculations efficiencies results and costs for the generation subsystems

VC	**FUEL (F) [MW]**	**PRODUCT (P) [MW]**	**IRREV. (I) [MW]**	η_B	**K**	δ	$K^*_{F_i}$	$K^*_{P_i}$
1	73,740	62,660	10,680	0,854	1,170	0,055	1,213	1,420
2	65,660	61,510	1,150	0,982	1,019	0,006	1,420	1,446
3	109,010	95,460	13,64	0,875	1,143	0,070	1,252	1,431
4	95,460	89,250	6,210	0,935	1,070	0,032	1,929	1,530
5	157,920	120,650	37,270	0,764	1,309	0,192	1,171	1,533
6	147,150	131,990	15,160	0,897	1,115	0,078	1,515	1,756
Cycle	194,110	110,000	84,770	0,567	1,765	0,433	1,000	1,765

According to Stambler (1993), the total installation cost of the CAES Plant was US$ 650/kW. In order to amortize this value it was considered a period of 10 years and an interest rate of 10% aa (www.bndes.gov.br). The conversion rate used was 2,4668 R$/US$ regarding August 10, 2001. The equivalence relationship was applied to acquire the yearly cash flow (Filho and Kopittke, 1988).

Also considering the fuel cost (natural gas), the electric power rate presented in Table (3), and admitting a unitary hourly consumption, the electric energy generation exergoeconomics costs were calculated in peak-load demand for the CAES Plant in the dry and humid periods, which results are presented in Table (11). Table (12) presents the conventional rate cost the subgroup B1 - Residential, and the Table (13) presents the sale price (kWh) in the wholesale energy market (www.aneel.gov.br) on August 13, 2001.

Table 11. Exergoeconomics electric power generation cost in peak-load demand for the CAES Plant simulation

Period	**Hour Seasonal**	**Cost [R$/MWh]**
Dry	Peak	201,1
Humid	Peak	198,0

Table 12. Subgroup B1 – Residential conventional rate

Conventional rate	**Consumption**
B1 - Residential	238,70

Source: www.cemig.com.br (Resolution nº. 126, April 05, 2001).

Table 13. Price of electric power sale price in the wholesale energy market

MAE Price – [R$/MWh]
Southeast and Midwest
184,17

Source: www.aneel.gov.br

5. Conclusion

As it can be observed at Table (11), the final cost of energy generation in peak-load demand in any period is smaller than the rates practiced by CEMIG as observed in Table (12). The value found for the CAES Plant is approximately 18% below of what is practiced by the company. Even with that advantage, it still should be considered the following points:

- The suitable rate in Table (12) is a practiced value that is independent of the peak-load or off-peak-load demand.
- This rate corresponds to the sale of electric power generated primarily by hydraulic base plants that are, most of them, already amortized, and therefore there is no need to amortize the installation costs, situation that was considered in the CAES Plant studied.

The hydroelectric base plants could assist the energy in peak-load demand, but for this, there would be the need to have spare electric power, what it's not the Brazilian reality.

If it had the possibility to built CAES plants near big residential areas the peak-load demand would be assisted so the hydroelectric plants could work only as base load plants. This together operation would level the electrical grid demand curve that would improve the electrical grid efficiency. This improvement would reduce the overload in the grid and therefore the blackout risk.

Another important analysis to be considered is the comparison of the energy generation cost of the CAES Pant with the values practiced by the wholesale energy market (MAE) as it can be seen in Table (13). The price practiced by the MAE is approximately 10% below what was found for the CAES Plant. This value can become a problem for an eventual competition for the electric power supply in peak-load demand. The possibility to make some technical improvements mainly in the subsystems 5 and 6 of the generation cycle, which are the largest irreversibility generators as it can be seen in Table (10), could cause a reduction of that price difference, which eventually would turn the CAES Plant a more attractive investment.

6. References

Filho, N. C., Kopittke, B. H., 1988, "Análise de Investimentos", Editora Atlas S. A., 8ª ed., São Paulo.

Kuhen, S. E., 1994, "Compressed Energy Storage Around the World", Power Engineering International, Vol. 2, No. 3, p. 39-41.

Silva, R. J., 1994, "Análise Energética de Plantas de Produção de Cimento Portland", Campinas, UNICAMP, Tese de Doutorado em Engenharia Mecânica.

Stambler, I., 1993, "World Utilities Going for Compressed Air Energy Storage", Gas Turbine World, Vol. 23, No. 1, p. 24-28.

Valero, A., Lozano, M. A., Muñoz, M., 1986, "A General Theory of Exergy Saving. I. On the Exergetic Cost. II. On the Thermoeconomic Cost. III. Energy Savings and Thermoeconomics", ASME Book nº H0341C, New York, p. 1-21.

Valero, A., Lozano, M. A., 1987, "Los Balances de Energía, Entropía, Exergía y Energía Libre", Ingeniería Química, Mayo, p. 143-153.

Valero, A., Lozano, M. A., Serra, L., 1993, "Structural Theory of Thermoeconomics", ASME Book nº H00874, New York, p. 189-198.