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Energy Efficiency and Heat Generation an Integrated Analysis of the Brazilian Energy Mix

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Abstract – *The Brazilian model for power generation presents very particular characteristics when compared to other countries in the world. Its great hydropower units allowed the country to indiscriminately use electricity for obtaining heat. However, this electricity can now be replaced by different energy sources of chemical origin. This research aimed to identify the distortion in the Brazilian energy mix, as well as to assess the potential for primary energy saving bound to be obtained by replacing electricity by final energy transformed into useful energy through combustion, instead of orienting it to electric power generation. Estimations were conducted on the replacement of electricity by natural gas in thermal end-uses of the different consumer sectors. Moreover, a comparative analysis was conducted on the energy mixes among the different countries in the world, concerning useful energy in the form of heat, so as to estimate the electric power percentage that could be replaced in Brazil and the amount of energy destined to an equivalent combustion chemical reaction. The possible environmental gains deriving from such a replacement were also analyzed. The results obtained show the relevance of the theme and the impact that could be attained by the rational use of energy.*

Keywords – Energy efficiency, energy planning, natural gas.

1. INTRODUCTION

The vast Brazilian hydropower potential, exploited in the past decades, directly contributed to the industrialization and to the economic development of the country. However, with the necessity to diversify the power generation, the participation of other sources of energy in the Brazilian energy mix has increased every year, specially that of natural gas. The great hydro potential still unexplored is, in general, distant from the main consumption centers and located in flatted areas, normally with hard environment and social restrictions.

The recent conclusion of the Bolivia-Brazil gas pipeline (Gasbol), the current main source of natural gas for Brazil, and the discovery of new gas fields in the Brazilian territory, especially in Santos field - southeast region - provides strong perspectives for a massive insertion of natural gas in its energy mix. What can be observed is a gradual transition from the hydro model for power generation to a mixed model, in which other sources of energy also have been showing relevant participation on the overall primary energy consumed [1].

The hydro model allowed Brazil to indiscriminately use the abundant power generated, without establishing priority uses. In the countries with a mixed generation model, power is prioritized for end-uses requiring more ordered energy, such as motor power and lighting, instead of electrothermics (use of electricity to obtain heat). In these countries, the production of useful thermal energy is mainly obtained by the chemical reaction of combustion and not by electricity.

This behavior occurs due to the possibility of using the combustion reaction both for power generation and for direct heat production (Figure 1).

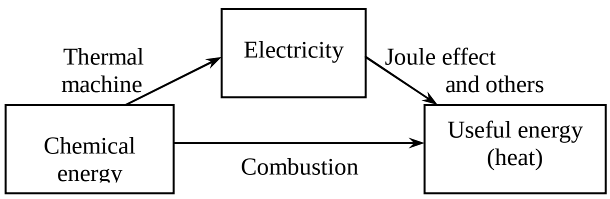

Fig. 1. Possibilities for using chemical energy for heat production

The obsession for broadening power supply, aiming to exclude the risk of new rationings and to provide greater stability to the system, may lead to a distorted model for rational use of energy. The current energy policy in Brazil concerning sources of chemical energy like natural gas has disregarded the great potential for primary energy saving which can be obtained by the use of final energy for thermal energy production by means of combustion, as a substitute to electricity.

The energy efficiency programs historically only used the concept of the First Law of Thermodynamics when analyzing energy conversion processes, giving little relevance to the thermal yields deriving from power generation. Furthermore, little attention has been given to researches aiming the development of public policies with this focus.

This work presents this approach, incorporating the systemic view to the planning phase. The methodology presented in this work allows identifying the existence of a real energy efficiency paradox, when considering the discussion of energy models and not only of specific

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processes. The results obtained present important subsidies for both policy formulators and decision makers.

The hypothesis formulated in this work is that the "rational use of energy, according to its quality and purpose of use, may significantly reduce primary energy consumption". Based on yields of the First and Second Laws of Thermodynamics, the global efficiency of processes demanding heat for the different consumer sectors were analyzed, involving all the stages of the energy chain: primary energy - final energy - useful energy (heat). From this analysis, proposals for rational use of energy are presented, aiming to provide new elements to the Brazilian energy planning.

2. AIMS

- To provide elements for establishing a new planning model for thermal energy use;
- To present the importance of the rational use of energy for energy planning, concerning the quality of the conversion processes, and the purpose of energy use;
- To propose an analysis and calculation methodology to estimate the possible primary energy saving potential to be obtained by the replacement of electricity by final energy destined to combustion, in thermal end-uses, and to identify, from the energy point of view, the priority sectors for such replacement;
- To compare the use of energy for heat production in Brazil, with its use in other countries; and
- To evaluate the distortions present in the Brazilian energy mix as well as to propose guidelines for the development of new energy policies.

It is worth observing that the aim was not to conduct an economic or a thermodynamic analysis; however, the results presented indirectly contemplate those factors and contribute to identify the priority sectors for the development of specific energy efficiency programs and to subsidize next papers regarding those issues. The intention was not also to compare hydro with chemical energy, but the different uses for the chemical energy, considering its forecast in the Brazilian energy mix.

3. HISTORICAL ASPECTS

Many countries, after the two great oil crises that occurred in the 1970s, tried to reduce the international dependence of their economies on the drastic price oscillations of the product. The main strategies adopted were: to increase the energy efficiency of energy conversion processes; and to replace the consumption of fuel oil in conventional plants (steam cycle) by other sorts of fuels or of plants.

Thus, the coal and nuclear thermopower generation was prioritized in many countries. After the 1980s, natural gas began to be widely used for combined-cycle power generation, very much increasing its final power. Other sources of energy, such as wind, solar and biomass, started to occupy specific market niches in some countries. Another form of protection found was to sign bilateral contracts for oils purchases and sales, and to expand internal exploitation. Moreover, many countries also massively invested in energy conservation programs [2].

In the case of Brazil, the above-mentioned oil crises generated the perception that a new energy policy was necessary. The country urgently needed to reduce its external dependence and to protect its economy from the unexpected oil price oscillations. The new Brazilian policy contemplated the following aspects: intensification of oil prospection; increment in the country's coal production; launching of the Brazilian nuclear program; establishment of the National Ethanol Program (Proalcool); continuity to the expansion of the hydropower generation complex; and the conduction of the first energy efficiency programs at national level. With special regard to the latter, the Brazilian Government even instituted a specific program to reduce the dependence on oil, called CONSERVE (Preserve). Among its measures, this program strongly stimulated the replacement of oil byproducts by electric power, in processes of thermal use of energy, both for direct heating and for process heat [3].

As from the 1990s, Brazil began the privatization of the power sector and the construction of Gasbol, inserting natural gas as a strategic source for the balance of its energy mix. Nevertheless, in an effort to solve immediate economic problems, the country adopted energy models from other countries for its natural gas policy, ignoring the fact of being in another energy paradigm, that of hydropower. A clear example of these actions was the Thermopower Priority Plan – PPT which, despite not having attained the expected success, provided a clear sign from the Brazilian government about the priority established for natural gas, that is, power generation, instead of its diffuse use, as reinforced in [4]. Despite the recent natural gas crisis between Bolivia and Brazil, the Brazilian strategy for its use, in general, remains the same. The planning for the use of chemical origin sources still aims at electrical generation.

Therefore, as useful energy in the form of heat can be obtained by means of final energy combustion (e.g.: natural gas, coal, oil and biomass), attention has to be given to the change in paradigm, both systemically and with interdisciplinary [5]-[7], so as to take adequate technical decisions for developing rational energy-use programs. A change in energy model must always be linked to the conformation of new strategies for primary use, in harmony with the change in scenario, observing both the First and the Second Law of Thermodynamics in the analyses.

The concept of the First Law of Thermodynamics is extremely useful for being able to evaluate and improve energy efficiency in end-uses equipment, as observed in the studies [8]-[10]. However, the Second Law of Thermodynamics should be considered in energy conservation programs, too, a fact also observed in [11]. The level of ordered energy, given by the entropy and exergy concepts [12]-[14], has to be adapted to the desired form of useful energy, improving the quality of the energy transformation processes (exergetic quality) and contributing for reducing losses in the energy mix as a whole. This work methodology was motivated by these presuppositions, described as follows.

4. METHODOLOGY

The calculation methodology elaborated aims to technically estimate the potentials for energy saving obtained by the replacement of electricity by chemical energy, in thermal end-uses of the Brazilian energy mix.

To estimate such replacement percentage, a second calculation methodology was conducted, based on international power consumption data. This methodology allowed incorporating an estimation of the technical feasibility of the replacement mentioned to the results initially obtained, with economic sensitivity, by means of a comparison between the Brazilian energy scenario and that of several other countries, specific for each consumer sector.

The losses of energy in transmission and distribution were not considered, neither were those in production, transportation or distribution of chemical energy, because it dependence of each considered country. The fuel used as conversion reference, both for chemical energy into electricity, and for final energy into useful energy, was natural gas, due to its strong perspective for insertion in the Brazilian energy mix, as mentioned before.

Database Used in the Methodology

The main literatures used as databases for developing this work were: Balance of Useful Energy - BEU [15]; Energy Balances from the International Energy Agency - IEA [16], [17]; and National Energy Balance - BEN [18].

BEU was a study conducted by FDTE - Foundation for the Development of Engineering, requested by the Ministry of Mines and Energy - MME, viewing the production of a reliable energy database, which would make possible to estimate the impact that the energy efficiency programs might attain on the reduction of final energy consumption. In order to elaborate this database, FDTE conducted a survey in more than 350 companies, besides using data from its former studies, elaborated by IPT - Institute of Technological Research, COPEL – Paraná State Energy Company, CEMIG - Minas Gerais State Energy Company and by other companies. More recent and detailed studies for the level of approach in this work could not be found, which may slightly limit the accuracy of results presented, without, however, harming its magnitude.

The IEA Energy Balances are among the most respected databases in the world in the energy area. BEN, in turn, is a work periodically published by the Ministry of Mines and Energy - MME, traditionally serving as a base for the Brazilian Government energy planning.

The three databases subsided the elaboration of a calculation matrix on which the data were compiled, with the due methodology adaptations. The methodology equations here proposed were applied to this matrix.

Analysis of the Thermopower Use in the Brazilian Energy Mix

For being able to compare the use of electricity for heat production, in relation to its replacement by a chemical energy source, it is known that the useful energy in the form of heat (U) produced by electric power to be substituted (E_s) will be the same as the useful energy of the equivalent chemical energy (Q_{eq}); that is, the chemical energy that will compensate the reduction in electric power destined to heat production (Equations 1, 2, 3, 4). This analysis considers the same baseline scenario in terms of demand composition of useful energy. The values of the energy transformation yields (η_{1e}, η_{1q}) were obtained from the mentioned BEU, considering each consumer sector and the average required temperatures. The value of E_s was estimated based on an international comparative analysis, according to the methodology as follows.

$$U = \eta_{1e}\ E_s \tag{1}$$

$$E_s = \frac{U}{\eta_{1e}} \tag{2}$$

$$U = \eta_{1q}\ Q_{eq} \tag{3}$$

$$\eta_{1e}\ E_s = \eta_{1q}\ Q_{eq}$$

$$Q_{eq} = \frac{\eta_{1e}\ E_s}{\eta_{1q}} \tag{4}$$

Although natural gas was used as a reference, any other source of chemical energy might have been adopted, sufficing to alter the values of the yields of transformation of final chemical energy into heat (η_{1q}) for the respective source desired. Such values can be obtained from the BEU.

Comparing the difference between the primary energies consumed in each process, it is possible to calculate the potential for primary energy saving (P) resulting from the replacement of electricity by chemical energy (Equation 5). The primary chemical energy is the very final chemical energy equivalent (Q_{eq}), once the sources of chemical energy, such as natural gas and coal, are primary sources. However, in the calculation of primary energy corresponding to the final electric power (P_e, Equation 6), the thermal yield of its generation (η_t) should also be considered. This was done as the electricity replaced (E_s) was considered to be generated by a chemical energy source. Taking Equations 5 and 6, Equation 7 is obtained.

$$P = P_e - Q_{eq} \tag{5}$$

$$P_e = \frac{E_s}{\eta_t} \tag{6}$$

$$P = \frac{U}{\eta_t\ \eta_{1e}} - \frac{\eta_{1e}\ E_s}{\eta_{1q}} \tag{7}$$

The thermal yield (η_t) adopted was 40%. This value was estimated according to the real average efficiency of the gas plants in some countries, considered as references in thermopower generation, such as: USA, United Kingdom, the Netherlands and others. The values were estimated from the IEA balances and consist of a mix of different energy sources and technologies, for example: Rankine and Brayton Cycles.

It is possible to obtain better thermal yields than 40%, especially in Combined Cycles, functioning in specific conditions of temperature and pressure, at nominal potential. In the Combined Heat Power (CHP) the efficiency can be even higher and it is a recommendable technology to reduce thermal energy losses. However, in a Simple-Cycle gas turbine system the efficiency is lower than 40%, generally 33% in ideal operating conditions.

The predominant technology that should be used in the Brazilian new projects is Combined Cycle, which should operate under its maximum potential of efficiency. Moreover its capacity factor is very low and with variable functioning, due to the features of the Brazilian energy mix. These features mean predominance of hydropower on flat operation and thermopower on the complementary supply. Therefore, considering specifically the natural gas use, to adopt η_t = 40% as an exercise should be a reasonable target for Brazil.

It is now necessary to know the amount of electric power (E_s) bound to be replaced by the energy obtained by combustion. This value represents a fraction of the final total electric power (E_t). Thus being, it is possible to obtain a percentage of replacement (S) for each consumer sector, as in Equation 8.

$$S = \frac{E_s}{E_t} \tag{8}$$

As Equation 7 is linear, in a theoretical analysis, it is easy to estimate the potential for primary energy saving for any percentage of replacement of electricity (S) by final chemical energy. Thus, it is just necessary to estimate the values of S that meet the technical and economic viability criteria for each consumer sector.

In an analysis restricted to a certain industry, it would be possible to estimate such value by surveying the amount of electricity consumed, the pieces of equipment used in the factory, the technologies available for their conversion or replacement, and other factors, such as the availability of gas at competitive prices, the type of supply contract, the maintenance costs and the service life of the equipment. However, this method shows to be too complex and not very feasible for large scale estimations, specially in macro sector analyses. Therefore, an alternative calculation methodology was devised, based on the comparative analysis of the thermal energy use among different countries, for each consumer sector in the energy matrix.

Analysis of the Thermal Energy Use in the World

Based on data from the mentioned IEA balances, some comparisons were made among the different consumption sectors, in each country analyzed, so as to identify the distortions of the present Brazilian energy model and to estimate which would be the percentage of electricity bound to be replaced in Brazil.

It was identified that the use of energy in the world presents two standard behaviors. The first comprehends the countries counting on predominantly hydro or nuclear generation, which were named the “Electric Group” countries. Examples of “Electric Group” countries are: Norway, Switzerland, Sweden, Brazil and France. Whereas the second behavior aggregates the countries with intensive use of thermopower generation from combustion, presenting great demand for natural gas, coal and for oil byproducts. For this reason, these countries were called “Thermal Group” countries, such as: USA, Russia, China, Germany, Japan, the Netherlands, United Kingdom and others.

Table 1 demonstrates this behavior. It was defined that the “Electric Group” countries are those presenting the sum of hydro and nuclear generation and of imported electricity, above or equal to 90% of the total generated, whereas the “Thermal Group” countries present a sum below 90%. This division line was adopted based on the characteristics of each country, concerning the use of electric power in thermal processes. Obviously, the transition of any country from one group to another is a gradual and not abrupt process. The aim of this characterization was simply to identify certain world behavior standards. Countries with low energy consumption were excluded.

Table 1: Characteristics of generation complexes

	Countries	Total electricity generation * (TWh)	Type of generation*: Hydro + Nuclear + Imported electricity	Type of generation*: Thermal
Electric Group	Norway	11.03	99%	1%
	Switzerland	7.76	97%	3%
	Sweden	14.08	94%	6%
	Brazil	32.01	90%	10%
	France	45.14	90%	10%
Thermal Group	Venezuela	6.93	75%	25%
	Austria	6.08	74%	26%
	Canada	51.00	73%	27%
	Belgium	7.95	63%	37%
	Finland	6.95	58%	42%
	Hungary	3.48	44%	56%
	Spain	18.77	43%	57%
	Argentina	7.50	40%	60%
	Germany	50.90	39%	61%
	Japan	90.90	38%	62%
	Chile	3.30	37%	63%
	Russia	73.42	35%	65%
	United Kingdom	32.55	31%	69%
	Italy	25.96	29%	71%
	USA	339.99	28%	72%
	Mexico	16.59	26%	74%
	The Netherlands	9.39	24%	76%
	India	45.47	18%	82%
	China	109.99	18%	82%
	Greece	4.41	12%	88%
	Denmark	3.79	12%	88%
	South Africa	18.00	10%	90%
	Australia	17.46	8%	92%

* Data sources: [16]-[17]

In fact, “Electric Group” countries use electric power without greater restrictions for obtaining useful energy in the form of heat, as usually the cost of electricity is relatively low and there is no alternative available, since neither hydro nor nuclear power could be used as final energy. On the other hand, in the “Thermal Group” countries, electricity is prioritized for nobler uses; that is, in processes where energy with better quality is needed, such as: motor power, lighting, electrochemical and others. In those countries, the use of combustion for counting on heat as useful energy is more widely observed.

It is observed that the “Electric Group” countries present, on average, a greater participation of electricity than the “Thermal Group” countries, for most of the consumption sectors (Figure 2).

The only dissimilar sectors were: Food and Tobacco; and Paper, Pulp and Printing. In these sectors, it was observed that the use of biomass has excessively increased the participation of chemical energy in relation to the overall, especially in Brazil. For most sectors, however the differences found were derive basically from the way countries use energy, according to its quality and purpose of use. It should be pointed out that only the countries satisfying the minimal requirements presented in the methodology below were considered.

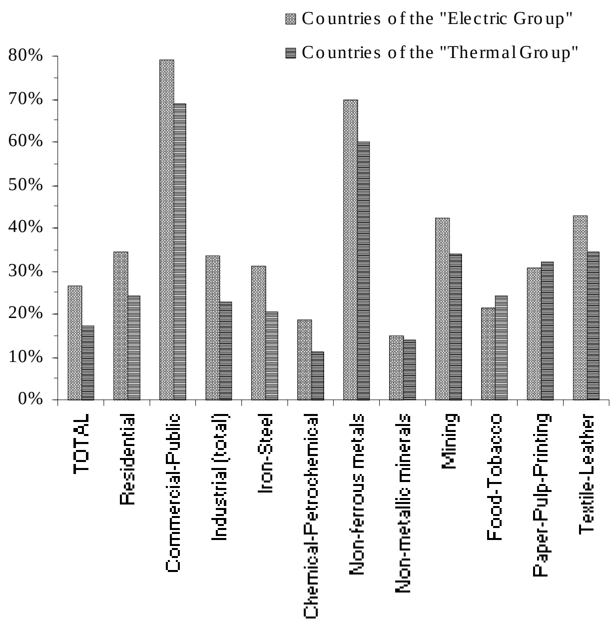

Fig. 2. Participation of electricity in the total energy consumption, for different types of generation complex

If the energy efficiency of the conversion of electricity into thermopower (η_{1e}) is usually superior to the efficiency of the conversion of chemical energy into heat (η_{1q}), what would the reason be for not prioritizing the consumption of electricity for heat production? Should the Government not conduct policies of intense use of electricity in thermal end-uses? In certain cases, the data show that this argument is valid for "Electric Group" countries, since they do not count on another relevant option for primary energy use, except for its conversion into electricity.

Nevertheless, for most cases, that is, for "Thermal Group" countries, it can be observed that the use of primary energy destined to the production of useful energy in the form of heat is usually much more interesting than for power generation, once the thermal yield of the thermopower plants (η_t) should also be considered. In these countries, the diffuse use of the chemical energy sources is very common and electrothermics is restricted to the situations in which electricity is really necessary, since there is a thermopower market for which chemical energy fails to replace electricity, owing to the technological limitations or to the existence of economic and environmental barriers.

Another exception can be made to heat pumps, where the use of electricity for heat production is very efficient. The heat pump was conceived by Lord Kelvin, in 1852, and basically follows the circuit of a Carnot heat engine. Its working is possible due to the input of two energy flows (heat and work) into a system and the output of one flow (heat) only, resulting into a performance coefficient above 1 [19].

Respecting the specificities of each technology, as a country alters its energy mix, increasing the participation of chemical energy in generation, planning should prioritize, in advance, the direct use of primary energy in the thermal end-use. At present, different countries are in this situation or in an inverse situation, that is, increasing hydro or nuclear participation in generation. Both should be alert to the need of gradually altering their energy planning models, in what concerns to the use of thermal energy. Obviously, the alteration of a mix is always associated to issues involving the supply and demand of energy resources; therefore, the energy efficiency issue will serve only as a basis for energy planning, since the technical viability, economic and environmental analysis, according to each enterprise, will actually determine the alteration process.

In the case of Brazil, with the increase in natural gas participation in the national energy mix, the country should tend to a gradual alteration in its energy planning model, that is, the electricity utilized in thermal processes should gradually be replaced by gas. In this way, there would be a reduction in the electric demand and a significant gain in energy efficiency, once gas would not be being used for generation. By the way, several studies conducted in the 1990s showed the existence of a wide market for gas in thermal end-uses. The papers [20]-[25] should be pointed out.

Calculation Methodology to Estimate the Replacement Percentage (S)

For a certain consumer sector of a given country, the total energy consumed (T) is the result of the sum of the electricity consumption in this process (E_t) and of the total consumption of other sources of energy (Q_t), according to Equation 9. Equation 10 expresses the percentage of electricity participation in relation to the total energy consumption.

$$T = E_t + Q_t \tag{9}$$

$$C = \frac{E_t}{T} \tag{10}$$

Analyzing the electricity consumption percentage (C) of each consumer sector, it can be verified whether or not a certain country uses electricity intensely. Thus, it can be concluded that the reference percentage would be the percentage which Brazil should attain, so as to be able to present an efficient use of its electricity, faced with the perspective of gradual transition from its hydro model to an increase in the participation of thermal generation, specially with natural gas.

Thus, to attain the reference percentage (C_{Ref}) it would be necessary to replace a certain amount of electricity (E_s) and to increment this deficit with chemical energy (Q_{eq}), once the consumption of useful energy in the form of heat (U) should remain constant in this case. Therefore, based on the equations described before, one comes to Equation 11.

$$C_{Ref} = \frac{E_t - E_s}{E_t - E_s + Q_t + Q_{eq}} \tag{11}$$

The value of *C* was calculated according to two estimations: aggressive and moderate. In the aggressive estimation, the smaller value of C found was considered as reference percentage, among all the countries analyzed, for a given sector. In the case of moderate estimation, the reference percentage is the average the C values of the countries that presented a value inferior to the Brazilian percentage. Since the value of Q_{eq} is given by Equation 4, isolating variable E_s of Equation 11 and considering Equation 9, Equation 12 is given, which expresses the amount of electric power that can be replaced by final chemical energy in thermal end-uses. Once the value of variable E_s is measured, it is also possible to calculate the percentage of replacement (S), for each sector of the Brazilian energy mix, as already described in Equation 8.

$$E_s = \frac{\eta_{1q}\left(C.T - E_t\right)}{C_{ref}\left(\eta_{1e} - \eta_{1q}\right) + \eta_{1q}} \qquad (12)$$

So as to exclude the countries with little representation, in each consumer sector analyzed, only the countries that showed to have tradition in the field and which presented a total energy consumption (T) above 10% of the Brazilian consumption were considered. This was done since small consumers could distort the analysis for presenting scales incompatible with the Brazilian scenario. The 10% value was adopted owing to the frequent gaps in consumption of some countries, as related to the average of the other countries. Furthermore, for the residential, agricultural, commercial and public sectors, the countries with climatic scenarios very different from that of Brazil were also removed from the analysis. For these sectors, the values estimated must be seen with reservations, once the replacement potential calculated could present a marked variation, in case field researches were conducted. This behavior does not occur for the industrial sector.

Figure 3 summarizes the composition of the variables presented.

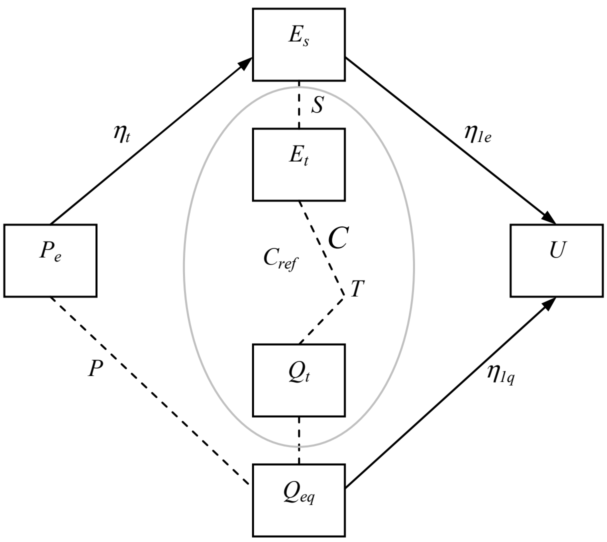

Fig. 3. Energy flow and composition of variables

5. RESULTS AND DISCUSSIONS

As a result of the international analysis, it could be verified that the participation of electricity in Brazil, in relation to its total consumption, presented a behavior close to those of the Electric Group countries, for most consumption sectors. The gap between the groups occurs mainly because of the use of electricity or of chemical energy for thermal ends. Thus, it was assumed that the difference found between the power percentage (C) of Brazil and that of other countries, from either the Electric or Thermal Group, basically represents the potential for inserting chemical energy as a replacement for electricity used for the production of useful energy, in the form of heat. Two potentials were estimated, the first (moderate potential) refers to the difference between the Brazilian power percentage and that resulting from the average of the countries with an inferior percentage to that of Brazil. The second (aggressive potential) compares Brazil to the country with the lowest power percentage, for each consumer sector. The values obtained are represented in Figure 4.

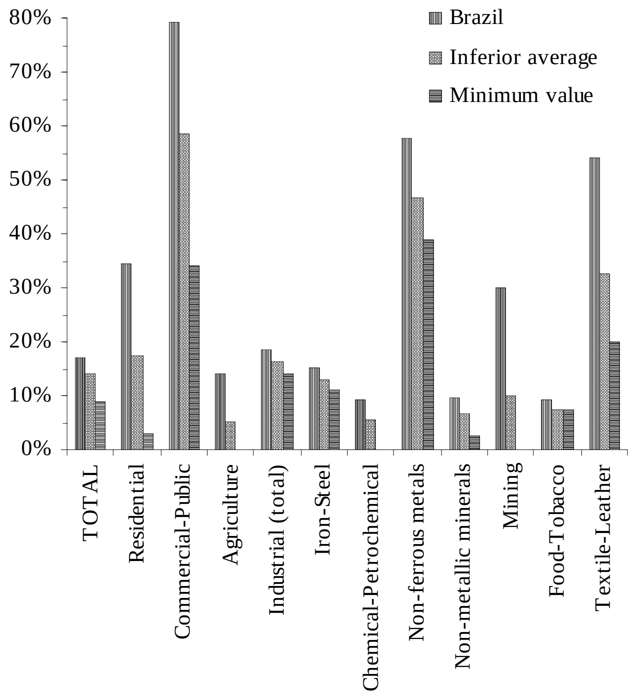

Fig. 4. Perspectives for replacement of electricity by chemical energy (electricity / total)

The inferior average and the minimum value represent reference values for Brazil, and incorporate the technological and economic dimensions of the countries considered in the analysis for each sector. Therefore, the maximum theoretical potential for electricity replacement by a chemical origin source may be even greater than the results obtained by means of the reference scenarios.

Based on Figure 4 and on the values of S estimated for each sector, one obtains Table 2, which presents a summary of the main results obtained.

As can be observed, both the aggressive and the moderate potentials for primary energy saving are extremely significant, in order of magnitude. The aggressive potential represents 58% of the energy consumption in thermal end-uses and 11% of the total energy consumption, whereas the moderate potential represents about 30% and 6%, respectively. The total energy consumption in thermal end-uses is equivalent to 18% of total energy consumption, considering all the electricity end-uses.

Table 2: Summary of results (values in 10^3 tOE/year)

Final consumption sectors	Power Consumption		Percentage of replacement (S)		η_1**		E_s		Q_{eq}		Primary energy saving potential (P) η_t = 40%	
	Total*	Thermal uses	Mod.	Aggr.	el	q	Mod.	Aggr.	Mod.	Aggr.	Mod.	Aggr.
Industrial (total)	11022	2606	*17.9%*	*36.0%*	*0.62*	*0.64*	431	788	433	785	643	1184
Iron and steel	1536	1111	14.4%	27.9%	0.56	0.69	160	310	130	252	270	523
Non-ferrous metals	2118	495	18.5%	31.6%	0.55	0.50	92	156	101	172	128	219
Non-metallic minerals	557	56	31.0%	72.4%	0.60	0.53	17	41	20	46	24	55
Mining	566	39	66.7%	100.0%	0.63	0.59	26	39	28	42	37	56
Chemical and petrochemical	1288	160	38.4%	100.0%	0.84	0.75	61	160	69	179	85	220
Food and tobacco	1286	298	21.2%	21.2%	0.87	0.74	63	63	74	74	83	83
Textile and leather	518	30	38.7%	62.2%	0.83	0.78	12	19	12	20	17	27
Paper, pulp and printing	943	53	0.0%	0.0%	0.94	0.88	0	0	0	0	0	0
Others in industry	2210	365	.	.	.	.	.	.	.	.	.	.
Residential	5902	1529	45.0%	90.0%	0.93	0.59	688	1376	1085	2169	636	1270
Commercial and public services	5837	410	20.2%	48.6%	0.83	0.56	83	199	123	295	84	203
Agriculture	1054	11	60.0%	100.0%	0.85	0.45	7	11	12	21	4	6
Energy	878	3	.	.	.	.	.	.	.	.	.	.
Transportation	101	0	.	.	.	.	.	.	.	.	.	.
TOTAL	24794	4557	*27.3%*	*55.8%*	*0.75*	*0.61*	1209	2374	1653	3270	1367	2663

* Data source: [18]
** Data source: [15]

For each sector, the potential obtained is conditioned to the replacement of equipment and to the alteration of specific processes of each activity. Only a detailed and *in loco* analysis can actually make the estimated replacements viable.

Considering natural gas as an energy product in Q_{eq}, it can be observed that, for a moderate estimation, gas presents an insertion potential of 1,653 ktOE/year or 1,878 million m^3/year. For an aggressive estimation, the value obtained was of 3,270 ktOE or 3,716 million m^3/year. As a comparison, the Gasbol maximum capacity is of approximately 30 million m^3/day or 10,950 million m^3/year [26].

So, the respective values estimated for the natural gas market correspond to 17% (moderate estimation) and 34% (aggressive estimation) of the Gasbol maximum capacity, which is very significant. The real value of this market will depend on the economic response to the investment for each technology, region and specific industry. It is necessary to explore each consumer sector in detail so as to obtain more accurate estimations. Nevertheless, the results found allow identifying the priority sectors for developing specific policies in this direction. In the case of natural gas, another important consumer market concerns the replacement of fuel oil and coal in thermal end-uses and of gasoline and diesel in the transportation sector, besides its use for electric power generation.

The use of CHP and other technologies, such as heat pump, may also alter some values obtained, though not affecting the magnitude of the results. Another limitation that has to be pointed out refers to the technological level of each country analyzed. This variation may be reduced, when considering countries technologically closer to Brazil, such as: Mexico, China, India, Argentina and others. Not considered, either, were the variations of the hydrologic cycle of the hydropower reservoirs, where thermopower generation may be strategic in some cases, for providing the Brazilian power system with more safety.

As to the environmental issue, with the presented data it is possible to obtain approximately the avoided emissions by the proposed energy policy change. Considering that Brazil inevitably will use more natural gas in the next years and will use it for electricity generation as a baseline scenario, it is possible to estimate the avoided emissions substituting its use for heat generation directly.

Both potentials for primary energy saving - aggressive and moderate - show possibilities for obtaining an expressive reduction of carbon dioxide (CO_2) and of nitrogen oxides (NO_x) emissions resulting from the energy policy change proposed in this paper. The particulate matter and sulfur dioxide (SO_2) emissions are not relevant in the case of natural gas and, therefore, were not considered in this analysis.

The emissions concerning the natural gas thermopower plants are of 449 tCO_2/GWh [27]; close values were also obtained by the Center of Natural Gas Analysis and Environmental Monitoring - Gaslab, of the Universidade Estadual do Mato Grosso do Sul, in Brazil [28]. For a moderate estimation of electricity replacement by natural gas, in thermal end-uses, there is a potential for primary energy saving of 1367 ktOE/year, approximately 1553 million m^3/year, which is equivalent to 15,891 GWh/year (860 kcal/kWh). Considering its use for thermopower generation, with thermal yield of 40% and capacity factor of 80%, one has 5085 GWh/year. Consequently, approximately 2.3 million tCO_2/year would cease to be emitted for a scenario of diffuse use of natural gas as a replacement for electricity, in thermal end-uses, instead of power generation. For an aggressive estimation, the amount to be prevented would be of 4.4 million tCO2/year.

In the case of NO_x emissions, the same Gaslab's paper mention that about 1 tNO_x/GWh (Gaslab, 2004) is emitted in an natural gas thermopower generation in combined cycle. Considering a moderate scenario of replacement of electricity by natural gas, the emission of approximately 5.1 thousand tNOx/year would be prevented. Likewise, for an aggressive scenario, the emission of 10 thousand tNO_x/year would be avoided.

The emissions data presented are just an exercise to show the magnitude of the results obtained, once the amount of emissions differs for each type of natural gas burning. The fugitive emissions for each case should also be computed. Nevertheless, it is possible to have a dimension of the economic and environmental advantages deriving from the rational use of thermal energy.

6. CONCLUSIONS

The Brazilian energy mix presents a high potential for inserting sources of energy of chemical origin to replace the electricity destined to thermal end-uses. By means of comparative analysis between Brazil and many other countries in the world, it was possible to estimate, for each consumer sector of the Brazilian energy mix, the respective percentages for the replacement of electricity by chemical energy. As a result, it was possible to prove the initial hypothesis that "the rational use of energy, according to its quality and purpose of use, may significantly reduce the consumption of primary energy". In fact, specific analysis regarding each energy conversion process, considering its involved temperature, exergy, entropy and anergy, must be explored in order to obtain more refined results.

The idea was to show the relevance of the proposed methodology, that was oriented to the macro energy planning, especially for policy makers. In this way, it was observed that Brazil presents several misleading or distortions regarding the thermal energy use in its energy mix, as it follows the restrictions of a hydro model for power generation, disregarding the consequences of its transition to a mixed model. The energy efficiency programs focus solely on the power end-use, disregarding the global efficiency of the conversion processes, which is a paradox. In the analysis of results, it was observed that many times it is more convenient to replace a certain source or form of energy than simply increasing the efficiency of certain equipment.

Concerning natural gas, its use as a substitute for electricity in thermal use processes showed to be significantly more advantageous than for electrical generation. The consumption of natural gas in Brazil with the implementation of thermopower plants should be better assessed, since its diffuse use provides a great potential for primary energy saving and avoids carbon dioxide and nitrogen oxides emissions according to the different energy policy strategies discussed in this paper.

As a consequence, with the expansion of thermal generation in the country, a new energy planning paradigm arises, in which the programs for rational use of energy must analyze, besides the First Law of Thermodynamics, yields the energy quality, according to its end-use. The decision makers and energy policy formulators must be duly oriented and alert as to the possibilities for primary energy saving derived from the rational use of thermopower.

The methodology proposed showed to be adequate and compatible with the aims of the work, and can be re-applied both in other countries and in regional analyses. In spite of the limitations found in the database, the results obtained contribute to identify the priority sectors and markets for developing specific public policies. The estimations conducted show the possibility of obtaining a significant primary energy saving as well as a reduction of environmental impacts.

New papers in this direction could contemplate the development of sector, regional or economic analyses, as well as database improvement. This work is expected to provide a basis for future studies and to contribute to the elaboration of a new energy-planning model for Brazil and for many other countries.

NOMENCLATURE

η_I	Yield of the First Law of Thermodynamics for transforming final electric power (e) or chemical (q) into useful energy, in the form of heat
η_t	Power generation thermal yield
C	Percentage of electricity consumption, in relation to the total consumption (x100)
C_{Ref}	Reference percentage of electricity consumption as related to the total consumption (x100)
E_s	Final electric power bound to be replaced by a final chemical energy source
E_t	Total final electric power
P	Primary energy saved
P_e	Primary energy corresponding to the final electric power destined to the production of useful energy in the form of heat
Q_{eq}	Final chemical energy equivalent to the electricity replaced
Q_t	Total final chemical energy
S	Percentage of electricity bound to be replaced by final chemical energy (x100)
T	Total final energy
U	Final useful energy, in the form of heat

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