Brazilian Hydroelectric System

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ABSTRACT

Electric power generation in Brazil is mainly based on hydropower (97% of total production in 1984). This paper describes the main features of the Brazilian Hydroelectric System as well as some power generation expansion possibilities. The operation of the system is also described, including a chain of scheduling procedures with different planning horizons and degrees of details in the representation of the system.

INTRODUCTION

Brazil is a large country covering about 8.5×10^6 km^2, with a population of 130 million, growing at a yearly rate of 2.5%. Annual gross domestic product totals about US$ 2000 per capita. The country is rich in water resources, particularly hydropower potential, but poor in fossil fuel resources. Although the present oil production has reached 500 000 barrels/day, this is roughly half the demand. As an oil importing country, Brazil has been severely affected by the oil price rises that started in 1973. For example, in 1980, when the national oil production was less than 200 000 barrels/day, the oil import costs were 50% of the export revenues.

The increase in oil cost would be much worse for the Brazilian economy if the production of electricity were oil dependent. Fortunately electric power generation in Brazil has been mainly based on hydropower. This was also the case for European countries, and to a lesser degree for the USA, at the turn of the century, when industrial production of electricity began. However, whereas in most of these countries the evolution of hydro generation has been supplanted by the corresponding evolution of fossil fired steam plants, this did not happen in Brazil. On the contrary, since 1910 the proportion of hydro has been consistently above 70% of the total electric energy produced.

Hydropower was an obvious choice for Brazil in the early days of electricity production because there were many good sites for power development in rivers located close to the main load centers; besides no oil or good quality coal deposits were known at that time. Nowadays the most economical hydroplants to be built are located far from the load centers and consequently some electricity is beginning to be produced by nuclear and coal steam plants. However hydropower production will still be the major source of electric energy in Brazil for a long time, probably for another 30 years at least [1].

HYDROELECTRIC PLANNING

Compared to other countries Brazil is an important electricity producer as shown in Table 1. Total installed capacity in December of 1984 was 42 GW (35.5 GW hydro and 6.5 GW thermal). During 1984 the total electric energy produced in the country was 168 TW h (97% hydro). During the period from '81 to '84 production kept growing at a yearly rate of 4.3% despite the severe economic crisis, due to the use of electricity as a substitute for fossil fuel in industry and also due to more than 3 million houses connected to the electric grid, many of them located in communities that were not previously served by electricity.

There are two large interconnected electric power systems, the South–Southeast and the North–Northeast, with no link between them. The major hydroplants (installed capacity higher than 1000 MW), in operation or under design, are shown in Fig. 1.

Most of the hydroplants of the South–Southeast system are located in the Paraná Basin, including the 12 600 MW Itaipu Binational (Brazil and Paraguay). This plant started to produce energy in October 1984, when two 700 MW units, out of eighteen, were put into operation. The transmission system from Itaipu to S. Paulo and other load centers is mixed, comprising three 750 kV AC lines and two ±600 kV DC lines, over a distance of about 800 km.

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TABLE 1

Electric energy production in 1981

Country	TW h	Country	TW h	Country	TW h
USA	2442	China	280	India	132
USSR	1306	France	276	Spain	110
Japan	523	Great Britain	260	Australia	105
Canada	379	Italy	191	Mexico	74
Germany (FRG)	377	Brazil	142	Korea	35

Source: National Energy Data Report, World Energy Conference.

Most of the hydroplants of the North–Northeast system are located on the S. Francisco River, but the latest plant connected to the system is the 3960 MW Tucurui on the Tocantins River. This is the first large hydroplant to be built in the North Region. Tucurui started to produce energy in November 1984 when two 330 MW units, out of twelve, were put into operation. A second stage is planned after which the total installed capacity of Tucurui plant will reach 8000 MW. Tucurui is an important component of the North–Northeast

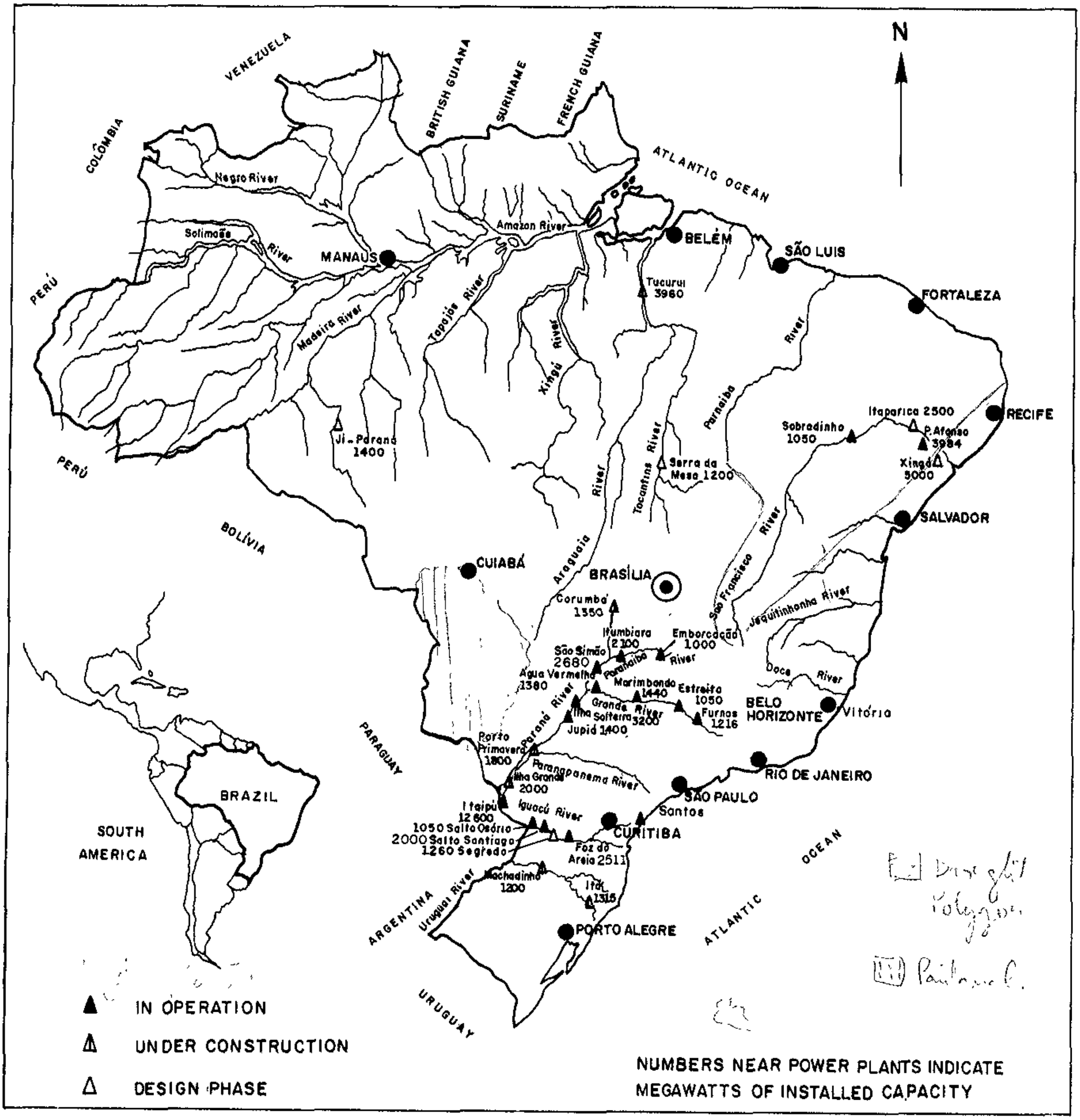

Fig. 1. Major power plants (installed capacity higher than 1000 MW).

interconnection, feeding a transmission system formed by 550 kV AC transmission lines, linking Tucurui to Sobradinho plant on the S. Francisco River, in the Northeast, and to the city of Belém, in the North, over a total distance of 1800 km.

These two hydroplants, Itaipu and Tucurui have some unique features. For example, Itaipu will have the largest installed capacity in the world and Tucurui the largest spillway capacity (Table 2). Energy produced by both plants has an estimated unit cost around 30 US$ per MW h.

There are several river basins in the country with a high hydroelectric potential. Table 3 displays some information regarding the four largest ones. ELETROBRAS (the Brazilian government holding power company) has developed a procedure to evaluate the country's ultimate hydroelectric installed capacity [2]. Since there is a large variation in the quantity and quality of data available for different river basins, the hydropower potential still available is classified into two classes (Fig. 2). The estimated potential results from preliminary studies, which for some basins is based only on the mean flow at the outlet of the basin and on the difference in elevation between the corresponding upstream and downstream sections of the reach. For other basins, when a river profile and a runoff–drainage area relationship are available, the estimation is based on the site properties of the probable hydroelectric developments. The inventoried potential is related to hydroelectric developments with sufficient hydrological,

TABLE 2

Main features of Itaipu and Tucurui power plants

	Itaipu	Tucurui
Installed capacity (MW)	12600	3960*
Drainage area (km^2)	820000	758000
Mean flow (m^3/s)	9070	11990
Maximum recorded flow (m^3/s)	33000	51521
Spillway discharge capacity (m^3/s)	62200	115000
Total reservoir storage (10^6 m^3)	29000	43000
Reservoir maximum surface area (km^2)	1350	2160
Firm energy production (TW h/year)	62	17
Mean energy production (TW h/year)	71	22

*In the second stage the installed capacity will be 8000 MW.

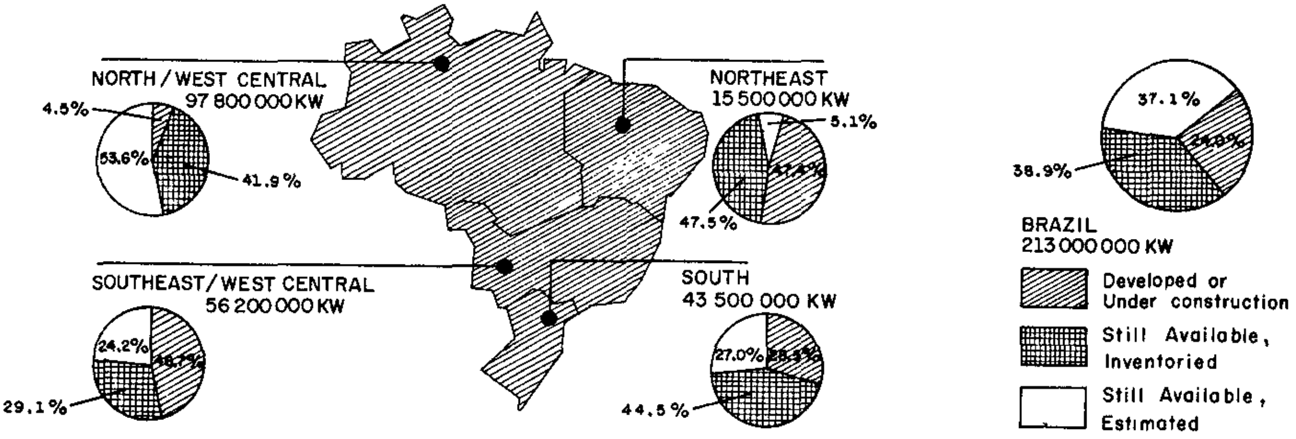

Fig. 2. Brazilian hydroelectric potential.

TABLE 3

Main rivers of Brazil

Basins	Drainage area (10^3 km^2)	Mean annual runoff (mm)	Main river	
			Length (km)	Elevation difference[d] (m)
Amazon[a]	6112	1080	2900	55
Tocantins[b]	757	477	2500	795
S. Francisco[b]	634	148	2800	1100
Paraná[c]	1245	257	2000	1000

[a] Amazon River flows from Peru to Brazil. Main river data are referred only to the Brazilian reach. The corresponding drainage area is 3900 × 10^3 km^2.

[b] Tocantins and Sao Francisco basins are all Brazilian.

[c] Paraná River flows from Brazil to Argentina and Paraguay. The data applies only to the Brazilian part of the basin (Paraná and Paraguay mag river.

[d] Elevation difference between the two extremes of the main river.

Source: Brazilian Hydroelectric Potential, ELETROBRAS, 1980 and Atuação, Brazilian Dept. of Water and Electric Energy, DNAEE, 1985.

topographical and geological information to support a preliminary design.

The procedure was later enlarged by OLADE, the Latin American Energy Organization, to fit the needs and procedures of the several countries of the region. In OLADE's methodology [3] the use of the gross theoretical capability is accepted. In this approach it is only necessary to have elevation maps and data on spatial distribution of runoff, often found through the mean annual isohyetal maps.

In the evaluation of the hydropower potential it is always assumed that the basic variable to be considered is the firm energy. This is defined as the maximum quantity of energy that can be delivered during each year, under the assumption that the worst hydrological conditions observed in the past will be repeated in the future. This is the most relevant feature for systems that use hydropower to meet the base load, like the Brazilian one. However since in predominantly thermal systems the main role of hydropower is to meet the peak load, hydropower potential is often expressed in terms of installed capacity. The relationship between firm energy and installed capacity depends not only on the hydrological conditions but also on the load variability of the system being considered, as it is necessary to assure the supply up to the highest peak demand foreseeable.

The Brazilian hydropower potential (estimated + inventoried + developed) expressed in terms of firm energy is believed to be 933 TW h/year or 106.5 GW year/year [2]. This is, from an energy standpoint, equivalent to an oil production of 5.6 million barrels/day, with the advantage that hydropower is a renewable source of energy. The ultimate capacity was assumed to be 213 GW, twice the firm energy expressed in GW year/year and implying an average load factor of 50%. Adopting the mean hydrological conditions observed in the past, rather than the worst, the produced energy would be 1195 TW h/year. In fact these estimates are probably smaller than the true values because pessimistic assumptions were embedded in the estimation methodology. Besides, basins with drainage areas smaller than 3000 km^2 in the Amazon region and smaller than 1000 km^2 in the rest of the country were simply neglected. It is worth mentioning that although the Amazon River has the impressive mean flow of 200 000 m^3/s [4] its hydropower potential is virtually null because there are no natural waterfalls. Artificial falls would be extremely expensive due to the Amazon River flatness. However there are many rivers in the Amazon basin which are well suited for electricity production. The Xingu River, for example, has several good sites for hydropower development along its 1500 km and a total drop of almost 800 m. One of them, the Altamira hydroelectric complex, will have an installed capacity of at least 15 000 MW.

Since the best sites for hydropower development in the south, southeast and northeast of the country have already been built, or will be built in the near future, plans are being made for the utilization of the hydroelectric potential of the north (the Amazon and the Tocantins basins). But building large plants is this region faces several problems:

First, because the region is largely covered by tropical forests, working teams cannot move freely in the jungle and airplane reconnaissance results in good pictures of the top of the trees rather than the ground altitudes. Besides, part of the vegetation in the inundated area has to be removed in order to avoid decay after filling the reservoir, which in turn may cause fish kills and damage to equipment.

Second, because the north region is sparsely populated, the only way to get workers to build the hydroplant is to bring them from distant places and from very different environments, with all the social consequences that this can cause.

Third, because historical records, particularly hydrological data, are available on very few places, even if one decides to measure water levels and water flows in the promising river sites (this has already started) the resulting time series will be long enough only when some of the dams have already been built. In order to overcome this difficulty, conceptual and regression models have to be used to extract information from the scarce data available, such as precipitation, basin's physiographic descriptors and streamflow records.

Fourth, because it is difficult to build very long (about 2000 km or more) transmission lines in the tropical forest environment, due to the fact that the main loads are still foreseen to be located in southeast and south regions.

Finally, because there are several Indian tribes in the north region, perhaps at the future dam locations, with very little or no contact with so-called civilization, getting in touch with these people without destroying them is no doubt a difficult task.

HYDROELECTRIC OPERATION

The energy production scheduling of each hydroplant of a system must be done taking into account the long-term effects (probability of future energy shortages, expected value of future thermal generation, etc.) and short-term effects (flood control, power capacity of each plant, etc.). Brazil has adopted a chain of scheduling procedures with different planning horizons and degrees of details in the system representation [4].

Although thermal plants account for only 15% of the installed capacity (1984), they play a critical role regarding operation cost and reliability of the hydrothermal system as a whole. Thermal plants burn expensive fuel to heat the water into steam, which is used to move the turbines. On the other hand, the direct operating cost of the hydroplants can be neglected, since in this case the 'fuel' is plain water, which the river supplies free of charge. However streamflow input to the plants is a stochastic process and if, at the beginning of a 'dry sequence', there is not sufficient water in the reservoir system, it is quite possible that before the end of this sequence the stock will be null. In this case the energy demand will not be satisfied, even if one turns all the thermal units on.

Engineers in charge of the system operation have to decide periodically, say monthly or weekly, whether they will produce a higher energy output from the thermal plants, with immediate cost, or produce this output depleting the water stock. In the first case the water kept in the reservoirs may be used in the future in the event of a 'dry sequence'. This eventually means that the energy demand will be met and also, the most expensive thermal units will not be turned on. On the other hand, if it comes to a 'wet sequence' rather than to a dry one, some of the reservoirs will eventually spill and the amount of money used to pay for the fuel could simply be saved.

Since it is impossible to have perfect forecasts of the future inflow sequences, the operation problem is essentially stochastic. For systems provided with reservoirs with large regulating capacity, the time horizon of the operation planning may be several years. In the Brazilian case, it is typical to use a five year horizon (sixty monthly stages). The mass conservation of water input to and output from the cascaded reservoirs, and the water flow and power constraints of each hydroplant, impose a multitude of restrictions and links between the problem variables. It can be said that the operation planning problem is stochastic, involving multiple periods and multiple reservoirs [6].

Since the operating cost for a time interval depends on the difference between the energy demand and the total hydro production, a reasonable way of approaching the problem is to lump all the real reservoirs into a single ideal reservoir, the so called 'equivalent reservoir'. Treating the problem as stochastic, multiple period and single reservoir, one can develop a strategy that gives for each time interval and state of the equivalent reservoir the partitioning between hydro and thermal production [7].

Once a strategy for operating the equivalent reservoir is available, one can perform simulation studies to assess the energy reliability, effect of delays in the construction of new plants, shortage of fuel, etc.

The equivalent reservoir representation is reasonable if all the hydroplants are subjected to the same hydrological conditions. In this situation one can expect that the reservoir storages will evolve in a similar way, that is, if one of the reservoirs is spilling water it is likely that all of them will be also in the same condition and it is said that the equivalent reservoir is spilling energy. The same kind of reasoning can be made with regard to the emptying of the reservoirs.

The perfect integration of the electric network is another condition the system must fulfill in order to make the equivalent reservoir a reasonable model. In other words, it is assumed that there are no constraints to route the power produced by any plant to the consumption centers.

There are situations for which the equivalent reservoir model is clearly not appropriate. For example, the south and southeast of Brazil have quite different hydrological conditions and their electrical networks are linked through a transmission line with limited capacity. Since the amount of energy to be exchanged between the two subsystems is in this case as important as the bulk thermal production, one approach to the problem is to adopt two equivalent reservoirs, explicitly taking into consideration the transmission line. This approach leads to the problem of how to operate reservoirs in parallel, which can also be generalized to more than two subsystems. Once a strategy for operating the reservoirs in parallel is available, simulation studies are done to assess, for example, the worth of the transmission line, measured by the difference in the reliability of energy supply for the entire system when there is and when there is not a line.

Since the power capacity of each hydroplant is a function of the available head, power supply reliability studies are done through multi-reservoir models, which represent in detail all the plants and reservoirs, as well as the relationships among the variables. This type of model splits the total hydro production, defined by the single equivalent or n-parallel equivalent models, among the hydroplants. At each time interval this can be accomplished by assuming that the reservoir inflows are known, which makes the problem deterministic, single period (only the present time inter-

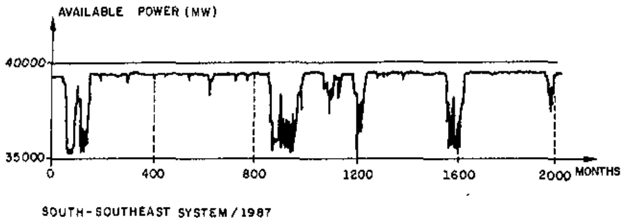

Fig. 3. Evolution of the available power in the Brazilian South–Southeast system (simulation with a synthetized streamflow sequence).

val is considered) and keeps the multiple reservoir feature of the original formulation [8].

Multiple reservoir models are often used in simulation studies, as for example the one shown in Fig. 3. In this case the interest was in the evolution of total power capacity of the South–Southeast hydroelectric system, planned to be in operation in the near future. The simulation was done using as input a 2000 month long synthetic sequence of water inflows to the hydroplants [9]. It can be seen that the loss of power capacity due to reservoir depletion reaches 10% of the total installed capacity. For this reason the reliability of the Brazilian electric system is more sensitive to water head variability in the reservoirs than to equipment outages.

Reservoir models are also employed to assess the interfaces between hydropower production and other water uses of river flow. For example, in recent years power utilities in Brazil have kept the water levels in the reservoirs below what would be the best from an energy standpoint, in order to avoid downstream flooding [10].

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